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The Geology of Western Cape Cod
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WOODS HOLE OCEANOGRAPHIC INSTITUTION

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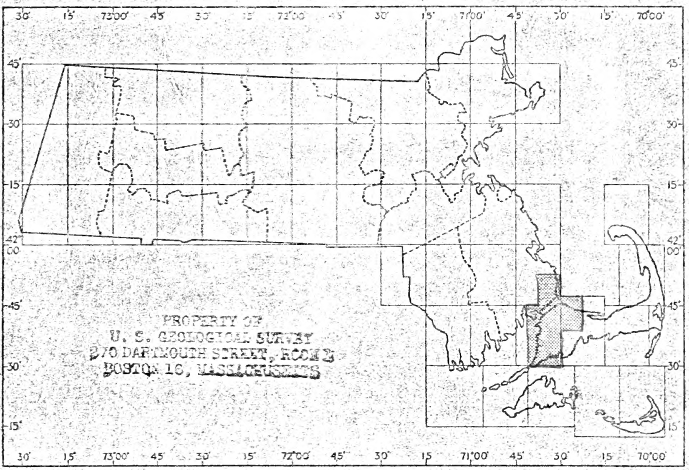
Massachusetts Department of Public Works
U.S. Department of the Interior, Geological Survey

COOPERATIVE GEOLOGIC PROJECT

Bulletin No 2

Preliminary Report on The Geology of Western Cape Cod Massachusetts

Kirtley F. Mather, Richard P. Goldthwait
Lincoln R. Thiesmeyer



Boston, Massachusetts
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Commonwealth of Massachusetts
Department of Public Works
H. A. MacDonald, Commissioner

U. S. Department of the Interior
Geological Survey
W. C. Mendenhall, Director

BULLETIN NO. 2

A PRELIMINARY REPORT ON THE GEOLOGY OF WESTERN CAPE COD, MASSACHUSETTS

by

Kirtley F. Mather, Richard P. Goldthwait
Lincoln R. Thiesmeyer

Prepared under a cooperative project for geologic investigations in the Commonwealth of Massachusetts

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PLATES AND FIGURES
(In back of the book)

A PRELIMINARY REPORT ON THE GEOLOGY OF WESTERN CAPE COD, MASSACHUSETTS

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Introduction

Geologists attempting to decipher the record of glacial times have long been interested in the features of Cape Cod and its neighboring islands. Technical reports[1] of their conclusions form an important part of geological literature. In recent years, through rapid development of the Cape as a vacationland, the opening of numerous pits, roadcuts and excavations has made available hundreds of exposures of subsurface materials that these investigators could not have seen. Storms, especially the hurricane of 1938, have cut back the cliffs at many places and stripped away slumped material that formerly obscured the geologic features. Excellent new topographic maps of southeastern Massachusetts are being made by the United States Geological Survey in cooperation with the Department of Public Works of the Commonwealth. Because the scale of these maps is larger and their contour interval is smaller, they provide a more accurate base upon which to plot the geologic features than did the maps used by previous investigators. Techniques in studying and interpreting geologic data have improved notably in the forward march of science. In recent years, geologists have been reporting an even greater complexity of glacial deposits in New England than had been previously inferred. It seemed advisable, therefore, to undertake a systematic re-examination of the geology in this critical and classic area.

The field work that forms the basis of this report was done during the summer of 1939, as a part of a continuing project for geologic mapping under the cooperative auspices of the Massachusetts Department of Public Works, and the Geological Survey, United States Department of the Interior. This report is designed to present to

[1] A selected group of these papers is listed at the end of this report. Reference to them will be made by numbers in parentheses indicating their position in the alphabetical list.

the intelligent lay reader in non-technical language the story of the origin and development of landforms and scenery of the areas mapped thus far. These include the newly-mapped Sagamore, Pocasset, Sandwich and Falmouth quadrangles, most of the Woods Hole quadrangle and parts of the Onset and Manomet quadrangles. (Fig. 1). This account embodies what is thought to be the best interpretation, in the light of modern geologic concepts, of all the facts known and inferred from study of these areas up to the present time. More technical discussions are planned for later publication.

Remapping of Cape Cod geology is continuing during the present year. Similar reports will extend this story into adjacent quadrangles. Thus it is intended that within a few years the citizens of the Commonwealth shall have available an authentic portrayal of the geologic history of the entire Cape region based on up-to-date maps and scientific studies.

The Table of Geologic Time

The history of any region prior to events observed by man is pieced together from records left by processes of nature in its geologic formations and landforms. No single area contains a complete record since earliest geologic time. At a place like the Grand Canyon in Arizona there are exposed vast thicknesses of rock layers that lie like a pile of manuscript pages, carrying the story of millions of years of earth history. Yet even here there are gaps in the record; pages are missing from the manuscript, because at some early date erosion gnawed at the top of the pile for a time and carried off whole chapters before later ones were written. Such interludes may be more fully recorded in a different locality, however, and diligent search is necessary to complete the chronicle.

Where sediments were laid down in layers and were not later overturned by some great earth movement, it follows that the sequence of the layers gives the sequence of events or conditions in their formation. It is possible, too, that layers in one part of an area were contemporaneous with those in another as, for example, the wind-blown sands of the Cape Cod dunes are contemporaneous with the beaches and bottom muds now forming in Buzzards Bay.

Periodically throughout the past the continuous flow of time has been punctuated by widespread upheavals of the earth. These caused interruptions in depositional processes and made possible the recognition of the units of geologic time, listed in what is known as the table of geologic time. It encompasses more than a billion years. (See Table 1). Its longer subdivisions are known as eras. They consist of periods which, in turn, may be separated into epochs. Numerous smaller divisions are discovered as geologic studies continue to unravel the complicated story of the earth's past.

In contrast to the Grand Canyon, Cape Cod has long been known to consist of only a relatively thin veneer of sediments formed in this part of the world during a very short and much more recent1/

1/ Note that this use of the word, recent, is not the same as its technical use in the time-table. In this report it will be capitalized wherever the restricted time interval of the table is intended.

episode, so that they are not yet consolidated into rock and may, indeed, be carried away by wave and stream erosion before consolidation can occur. Firmly consolidated rocks are not exposed anywhere on the Cape, but are believed to lie several hundred feet below the surface near Woods Hole, and may be nearly a thousand feet below at Provincetown. This report, therefore, is concerned with only the upper more recent part of the geologists' time-table, comprising but a fraction of the last million years of world history. Consequently all of the earlier, lower part of the accompanying time-table has been simplified and abbreviated.

Table I

The Table of Geologic Time

CENOZOIC ERA -- duration about 60 million years

Quaternary period

Recent epoch -- since the last glaciers of the Ice Age disappeared from New England; estimated as 20,000 to 30,000 years duration; may be only another interglacial stage of the Pleistocene.

Pleistocene epoch -- The Great Ice Age or glacial epoch -- duration about a million years.

(each may be further subdivided into sub-stages.)

- *4th glacial stage (Wisconsin glaciation) duration 50,000± years.
- Interglacial stage (Sangamon interglacial time) duration 100,000± years.
- 3rd glacial stage (Illinoian glaciation) duration 50,000± years.
- Interglacial stage (Yarmouth interglacial time) duration 300,000± years.
- 2nd glacial stage (Kansan glaciation) duration 50,000± years.
- Interglacial stage (Aftonian interglacial time) duration 200,000± years.
- 1st glacial stage (Nebraskan glaciation) duration 50,000± years.

Tertiary period -- the Age of Mammals

MESOZOIC ERA** -- the Age of Reptiles -- dinosaurs, etc., first birds; duration about 150 million years.

PALEOZOIC ERA** -- first appearance of nearly all the major groups of plants and animals; duration about 400 million years.

PRE-PALEOZOIC ERAS** -- beginnings of plant and animal life; numerous divisions; probably constitute the major parts of geologic time; duration at least a billion years.

*Some geologists subdivide this into two stages of glaciation, known as the Early Wisconsin (or Iowan) stage and the Late Wisconsin stage.

**These eras, like the Cenozoic, are also subdivided into numerous periods, but inasmuch as formations belonging to these periods are not exposed anywhere on Cape Cod, they are not listed in this table.

The Ice Age in North America

Origin of the Glaciers

Because most of Cape Cod and its neighboring areas are made up of deposits formed by glaciers of the Ice Age and their meltwaters, it is appropriate to consider briefly the origin and spread of these mighty ice sheets. Discussion of the causes of glacial climate is, however, beyond the scope of this report. This picture of the growth and expansion of glaciers is based partly on our knowledge of the behavior of glacial ice wherever it exists today, and partly on inferences drawn from deposits believed to be of glacial origin now found over broad tracts in the northern hemisphere.

About a million years ago, at the close of the Tertiary period, after a long interval of rather warm olimatic conditions throughout the world, the average temperature was everywhere lowered a few degrees. This initiated a cycle of colder, moister weather which developed into an Ice Age. Snow which fell during the winters at high altitudes and in northern latitudes was not completely removed by summer melting. The excess of each year accumulated on top of that of the preceding year. Packed down by the weight of snow heaped upon it, and altered in its structure by partial melting and refreezing, this snow turned to ice. The ice began to spread outward or move sluggishly downhill, under the weight of increasing accumulations of snow, just as do modern glaciers in the Alps or in the Rockies today. After thousands of years, the ice had piled up to such thickness that large areas of land were blanketed by far-flung sheets of ice like those which cover Greenland and Antarctica today.

These Pleistocene glaciers, like their modern counterparts, were thickest where the precipitation of snow had been heaviest, and became thinner progressively outward. Several such masses, shaped like inverted saucers and covering a total of many millions of square miles, formed in northern America, Europe, and Asia and reached thicknesses estimated as great as 8,000 feet at their centers. At the same time the Greenland and Antarctic ice fields were thicker and thousands of square miles broader under the cold Pleistocene climate than they are today. It should be noted that there were several separate ice caps, only two of which had their centers in the polar regions. Many people have a mistaken impression that the ice of the polar areas simply expanded and moved into temperate latitudes during the Ice Age, and that it has shrunk since then to its present dimensions.

These ice covers spread outward in all directions in some respects like thick molasses poured on a table. Their margins moved over the irregular land surface and extended far into warmer latitudes. Here they could persist only so long as the forward movement kept supplying as much ice as could be melted or evaporated away each day. With enormous tonnages of thick ice behind them, the advancing edges were able to ride up over hills and even in some places to cover low mountain ranges.

North America had three huge gathering-grounds of Pleistocene

ice: one over northeastern Quebec and Labrador, one over the Keewatin area west of Hudson Bay, and a third over the northern Rockies of Canada. Within a few tens of thousands of years, ice masses that had developed in these areas spread out to coalesce, interfinger or overlap one with the other. (Fig. 2). The southern margin of this compound ice sheet reached Long Island on the east, St. Louis in the central interior, and the Canadian border on the northwest where the motion was impeded somewhat by the rugged peaks of the western mountain ranges.

Motion of the Ice Sheets

The rates at which different parts of the ice crept over the land varied considerably from place to place and from time to time. We have no way of measuring the precise speed of advance except by comparison with the motion of modern glaciers, but it seems safe to conclude that it could generally have been measured in yards per month rather than in miles. Obstructions, slope of the ground, earthquakes, weather conditions, and amount of snow in the centers where its accumulation was greatest were important influences. In part the movement was probably like the slow, steady, viscous flow of a thick syrup, and in part a sort of interrupted, staccato skidding.

Naturally the ice would move more rapidly along valleys and would be protected from melting in them longer than it was on adjacent uplands and divides. Consequently the rims of the expanding glaciers became very irregular in outline. Large volumes of ice moved into major topographic depressions like the St. Lawrence valley lowland in the form of lobes that stretched far in advance of the main body of ice. Some of these lobes were large enough to spread laterally while they advanced, whereas thinner ones were confined within valley walls. During later melting and recession of the ice borders, these lobate shapes became even more pronounced.

Effect of Glaciation on Life

As the zone of more rigorous climatic conditions surrounding these glaciers moved outward, animals and plants unable to cope with the changing environment perished, unaware that the remote glaciers were dealing them a lethal blow. Other animals and plants sensitive to slight changes migrated far in advance of the oncoming ice, or retained their habitat for awhile by adapting themselves to the new conditions. There was no sudden evacuation, however, because the changes were very gradual, almost imperceptible to an individual generation. Nevertheless, even the hardier creatures finally yielded to the relentless onslaught of savage, biting winds that blew down across the ice and spread their chill influence for hundreds of miles ahead of the ice front. Some of these northern creatures took up residence in Florida. At the same time, the hairy ancestors of modern man were huddling and shivering in the caves of southern France. The land close to the ice was, however, not barren by any means. Rugged plants and arctic animals thrived in the vicinity of a glacier or

spread over its thin margins just as they do today in Greenland and Alaska. But they were immigrants living in territory far removed from their realms during non-glacial times.

Glacial Deposits

While the ice was accumulating in low areas and valleys, blocks of rock loosened from valley walls by strong frost action rattled down and landed on its surface. Torrents of rainwater washed great quantities of soil and stones onto it. Strong cold winds blew dust across its surface and it became dirty ice, much like that which develops some time after a snowstorm even today. This material was then covered with more ice and the process repeated. At the base of the ice or along the side walls underneath, loose soil, boulders, and blocks of rock were frozen into the growing glacier. As it moved, already charged with rock debris, it scraped still more material from the floor and sides, and plucked huge blocks from surfaces over which it rode. Soils in front of it were pushed into mounds, only to be overridden and incorporated, in part at least, in a mat of jumbled fragments in the lower part of the ice and beneath it. Material thus carried in the ice as it moved along, or by meltwaters derived from it, was destined to be deposited on the landscape during the process or when the ice melted. In places one may observe blocks or boulders that must have travelled many miles from their source. During the advance, the glacially-transported fragments acted as abrasives to scrape and polish bedrock ledges, scour clean and widen the bottoms of valleys, or scratch systems of parallel grooves on rock floors such as may be seen at thousands of places throughout New England. In this way the debris-laden ice crushed and pulverized much of the materials over which it rode and those that it was carrying. Many fragments that escaped crushing were rounded, polished, and scratched by the smaller particles as they were rolled among them or were dragged against sharp projecting edges of harder rocks locked in the icy grip of the glacier.

All along the irregular front of the ice at its farthest limit, a jumbled mass of rock materials was piled in low mounds and knolls to form a belt that now extends in snake-like curves across the countryside and marks the uneven limit of glacial advance. Part of it may have been shoved along like material in front of a plow, and part of it was merely dumped where it now lies as the ice border melted. Geologists call such a deposit of ice-borne materials a moraine.

A moraine may range from a few yards to several miles in width; and its higher parts may rise a hundred feet or more above its surroundings. At some places it may stand on level ground and elsewhere it may rise along the slopes of hills and mountainsides, its location determined by the position of the edge of the ice at the time of deposition.

Where the moraine is rather wide, it was not all constructed simultaneously, of course. Material dumped at one place was covered later with similar material by slight readvance of the ice or was pushed forward to new positions. The ice-edge oscillated back and

forth within a few miles, probably for centuries, each local advance bringing a fresh supply of debris. Masses of dirty ice became isolated and buried among the rock materials. When they finally melted and contributed their load to the moraine, the material above them slumped down and irregular hollows were formed on the surface. Such pits are known as kettles or kettle-holes. The surface of any marginal moraine is generally rough, partly because of the great number of such kettles and partly because of the irregular hummocks or knobs between them that result from abrupt variations in the thickness of the debris.

The geologist gives the name till to such a heterogeneous accumulation of unlayered (unstratified) material. Till usually consists of fragments of many sizes, from great blocks of rock to pulverized rock flour. This material was either dumped, or pushed ahead of, or plastered beneath a glacier. Till was also spread as a thin veneer over the land behind the outermost, terminal moraine either because it was laid there by the overriding ice during its advance or because it was let down slowly upon the surface when the glacier melted. The name ground moraine is applied to such bodies of till scattered over the area covered by the ice. The thickness of a deposit of till may vary a great deal. In some places whole hills are made of till, whereas nearby areas are free from any such covering.

Blocks and boulders carried by the ice were deposited at random over the glaciated tract. Those transported far from their source are composed of rock material that may be quite different from the bedrock underlying their present resting-place. Some rest in the midst of till masses or on top of them, and others are now perched atop naked rock ledges. Such ice-carried blocks are called erratics.

Even while the ice-sheets were increasing in size, parts of them melted during the day time and during the summer months, especially those portions that had reached low altitudes and warmer regions. The meltwaters were loaded with rock debris, and they deposited it in layers in front of the ice. Such material, known as outwash, consists of gravel, sand, and silt mixed with small amounts of clay. As it was transported partly by ice and partly by water, it may be called glacio-fluvial debris. The particles in it became rounded and smoother than the more angular fragments generally found in glacial till, because they were rolled and jarred against one another during water transport.

Some melting also occurred during the construction of the moraine so that masses of stratified outwash sands and gravels are occasionally found embedded in the till of the moraine. Small streams of meltwater piled conelike masses of outwash in front of the ice and resting against it. Sand and gravel also accumulated in hollows on the surface of the ice. When the glacier melted away from these masses, they stood as isolated hills known as kames. In places a whole series of them were built along the ice front so that they form an almost continuous, irregular ridge. Outwash also accumulated in broad, low, fan-shaped masses extending outward from the ice for several miles. Because of their gentle surface slope, such features are called outwash plains.

Deposits of all sorts formed by glaciers or their meltwaters constitute what is known as glacial drift. A land surface that has been glaciated is thus veneered with an irregular mantle of drift, which includes moraines, outwash plains, kames and erratics, as well as other types of glacial, glacio-lacustrine and glacio-fluvial deposits that need not be mentioned here, inasmuch as they are not represented in the area under consideration. The drift at any one place may, therefore, consist of either till or glacio-fluvial materials or both; and at some places the drift may include deposits formed during several successive stages of glaciation.

Retreat of the Glaciers

Whenever the climate of the Pleistocene became warmer or drier, the margins of the melting glaciers receded, even though the ice composing them may have continued to move forward. This retreat was induced not only by more rapid melting and evaporation of the ice, which caused a thinning and down-wasting of its border regions, but also by a reduced supply because of smaller accumulations of snow at the center. The glacier fronts receded, gradually uncovering the land and spreading vast quantities of outwash over it here and there. Lakes were formed where drainage was blocked by glacial deposits as well as in hollows on the irregular surface of the drift. Plants and animals repopulated the glaciated terrains, following closely behind the dwindling ice and spreading across the rocky, glacier-borne soils.

The ice recession was by no means continuous. There were spells of cooler weather within centuries of warmer conditions so that the glaciers pushed forward again for short distances, plowing and piling up debris they had previously dumped on the land. At times the ice front stood at almost the same position for scores of years because only as much new ice was pushed forward each year as was melted. Consequently, moraines were heaped up to mark places where the ice front remained practically stationary, just as they had marked the limit of maximum advance. Because this process was repeated frequently during the thousands of years of recession, a great series of these recessional moraines was strung across the countryside. In the central United States where the lands are relatively flat, these are easy to recognize; but in the mountainous country of the eastern areas and in most of New England, no such extensive systems of morainic belts have been observed.

Several Episodes of Glaciation

Geologists who studies the glacial deposits of North America and Europe during the latter part of the last century and the first part of this were soon convinced that during Pleistocene time the ice sheets formed and spread, melted and disappeared several times, and that the climate of the world was even warmer during some of the intervals between glacial episodes than it is today. They subdivided the Pleistocene, therefore, into stages of glacial advance and

interglacial stages, each lasting tens or hundreds of thousands of years. (See Table 1). In North America there were at least four distinct glacial stages, and possibly a fifth, each marked by deposits such as have been described in preceding paragraphs.

The areas covered during each glacial stage are not identical. It is possible, therefore, to distinguish terminal moraines of each stage and to find deposits of the earlier Pleistocene glaciations that were not overridden by later Pleistocene glaciers. Fortunately the tills of earlier stages were not everywhere plowed up and removed during readvance of the ice. Consequently, at some places we can find the sediments of several stages lying one above another, proving that these localities were subjected to repeated glaciation. It would not be easy to distinguish the several tills, however, if the older ones were not more rotted and stained because they lay exposed to weathering for a longer time. Here and there, layers of soil containing the remains of plants that could thrive only in warm weather have been found between till layers. This is clear evidence that after the ice that laid the lower and, therefore, older material had disappeared, vegetation flourished for a while and was then buried when glaciation prevailed once more.

Glaciation in New England

The veneer of glacial materials is thinner in the eastern United States than in the central states. Although the thickness of the till over the east is generally only a few feet, in places it may reach hundreds of feet. The bedrock of New England over which the ice had to travel is more resistant and did not yield so large a volume of crushed and pulverized material as the widespread shales and limestones of the interior. The hilly country of the northeast prevented the ice from spreading as far south. Perhaps, therefore, there was not so large a volume of till-bearing ice moving across a particular locality in a thousand years of each glacial stage. Possibly the climatic influence of the neighboring ocean in some way prevented the ice from becoming as thick as it was farther west; as a result there was less debris to scatter over the land surface.

A much greater variety of rock types is exposed in the maritime states than in the inland states. These rocks had been weathered so that soils of many colors developed on them during millions of years preceding the Ice Age. The till formed from these soils during any single stage of glaciation could not, therefore, be uniform in color and content from place to place. It is an uncertain procedure to identify a New England till as old, or early Pleistocene, simply because it looks badly rotted and stained.

The features attributable to glaciation in eastern North America have not received as much attention and study as have those in the Great Lakes region where bedrock geology is much obscured by glacial deposits. It cannot yet be stated definitely, therefore, how many times New England was ice-covered during Pleistocene time, nor can the areas covered during any earlier stage of glaciation be precisely designated.

Other complications in the glacial geology of this eastern land are attributable to its hilly topography. The hills were uncovered during ice recessions earlier than were the valleys between them. Long, narrow masses of ice stood stagnant in the valleys and became separated from the receding margin of the main glacier. As they shrank, their meltwaters were ponded along the sides against valley walls. Lakebed sands and silts which accumulated at many places in these temporary basins conceal whatever underlying glacial or glaciofluvial materials may have been spread there. During the later centuries of ice recession, New England must have been a crazy-quilt of till-veneered or barren hills alternating with stagnant ice masses and dotted with ephemeral lakes.

Change of Sealevel

A significant fact to keep in mind concerning the Ice Age is that the sealevel of the whole world stood 150 to more than 300 feet lower than it does today. The glaciers were fed by snow that could only have come originally from evaporation of seawater. As the ice increased in thickness, the sealevel went slowly down and the shoreline migrated out from its previous position. Conversely, during the interglacial stages enormous volumes of ice melted and returned their waters to the ocean; the sealevel rose and the shoreline crept back over the continental margins. Some authorities believe that the New England strandline may have moved over a hundred miles east of the present shore during the stages of glaciation.

Formation of Cape Cod by Pleistocene Ice Sheets

Age of the Deposits

More than a century ago, Hitchcock (3) described the abundance of scattered erratic boulders strewn over Cape Cod and adjacent islands, and attributed them to "the flood" of biblical history, but not without some uncertainty as to the adequacy of that explanation. Geologists have since recognized and proved that the Cape consists almost entirely of glacial and glacio-fluvial materials, and that its more prominent ridges are morainic in origin. They have suggested that these moraines are continuations of glacial features observed on Long Island, Rhode Island, and parts of eastern Massachusetts. Kirk Bryan (1) recently raised the question concerning the stage to which these deposits belong by suggesting that "Martha's Vineyard and parts of Cape Cod and the mainland of Massachusetts were free of ice in the late Wisconsin and perhaps even through the whole of Wisconsin time." Moreover, R.W. Sayles (5), working principally on the more easterly portion of the Cape, observed phenomena indicative of an even greater complexity of glacial and associated deposits than had been inferred previously.

From intensive studies of the areas mapped during the summer of 1939 and from reconnaissance trips over the rest of the Cape, the authors of this paper are already convinced that the major features of Cape Cod geology were formed during the later substages of the Wisconsin stage of glaciation because:

1. The till and associated glacio-fluvial gravels are, with few exceptions, not as hard and compact as one would expect them to be had they been overridden by later ice or subjected for a long time to cementation by ground water; and they are not as stained and rotted as they should be if exposed to a long interval of weathering.

2. The zone in which material was disturbed by frost heaving and the wedging action of plant roots and the zone of weathered soil at the top of the deposits are relatively thin, averaging together less than 3 feet. Such thin zones could not represent a long interval of disturbance and exposure to weathering.

3. Slopes produced by melting of buried ice blocks have been modified very little by slumping and rainwash, and the bottoms of kettles are almost free of surface fill which would have accumulated in them to considerable thicknesses had they stood open for more than a few tens of thousands of years.

4. Surface drainage has made very little headway in gullying and modifying the contours of the moraines and outwash plains. We would expect much more erosion of such loose materials in so long a time as that from Illinoian or early Wisconsin to the present.

Deposits that undoubtedly belong to early Wisconsin or earlier Pleistocene stages are exposed in some parts of southeastern Massachusetts, especially east and north of the areas included in this report. These may be seen in the lower parts of the cliffs on the north shore between Ellisville and Plymouth, north of Dennis, and from Chatham to Truro. Details concerning them must be deferred to

a future report after they have been mapped and studied in the continuation of field work.

It is believed, furthermore, that the deposits of western Cape Cod were formed during the waning and recession of the ice of the Wisconsin stage and that the moraines are, therefore, recessional moraines. The presence of hundreds of kettle-holes, many of them now occupied by ponds, that range up to a mile or more in length and width, throughout the south central part of the Cape makes this conclusion inescapable. They were formed because myriads of ice-blocks isolated from the retreating glacier stood in those localities, were covered by outwash and then melted away. Thus they show that considerable volumes of ice existed far south of the moraine fronts on the northern part of the Cape. The terminal moraine of the Wisconsin ice must have formed south of the moraines on Cape Cod, and is probably represented by the morainic ridges of Martha's Vineyard and Nantucket, as described by Woodworth and Wigglesworth (7) and others.

Wisconsin Terminal Moraine

In brief outline, the story of the formation of Cape Cod during the Pleistocene, based on conclusions from this study and on those of earlier investigators, is as follows: (See Fig. 3).

The ice of at least one earlier glacial episode of the Pleistocene reached this region and spread deposits which were modified and almost completely concealed by the advance of later ice sheets.

During Wisconsin time glacial ice extended southward from northern New England, moved over what is now the Cape and reached a terminal position on Nantucket, Martha's Vineyard, and Long Island. The margin of this ice sheet was pronouncedly lobate. One lobe stretched southwestward down what is now the Buzzards Bay trough, and another spread southward across the floor of Cape Cod Bay which was then dry land because of the lowered sealevel. According to J.B. Woodworth (7), a third lobe extended southeastward over the floor of what is now the eastern part of Massachusetts Bay and stood east of Provincetown and Chatham. The terminal moraine marking the maximum spread of this ice was built along a sinuous line looped from Nantucket to Martha's Vineyard to Block Island to Montauk Point at the east end of Long Island. A broad outwash plain was formed as a fringe along the south side of this moraine. Later the lower parts of the moraine and much of the associated outwash deposits, both north and south of it, were drowned when the sealevel rose again, but the higher portion may be observed on these islands.

Recessional Moraines and Outwash Plains

The ice front retreated many miles northward in response to changes in the climate and its lobate form doubtless became more marked. Masses of stagnant ice were left standing at many places in the uncovered area. Much of the record of the easternmost lobe has been obliterated by the rise of sealevel, but the other two lobes

left abundant evidence of their behavior on western Cape Cod. Their fronts receded to positions near the present north shore of the Cape and east shore of Buzzards Bay and remained there long enough to pile a huge outwash deposit, forming the Mashpee pitted plain, in front of them. This plain resembled a gently sloping fan with its apex somewhere northeast of Bourne at the junction of the two lobes. Then the ice advanced to ride up onto the northern and western edges of the pitted plain, and remained there long enough to pile the till of what is called herein the Buzzards Bay moraine and the Sandwich moraine over the outwash gravels. These moraines were considered as a single continuous unit by Woodworth, which he called the "Falmouth moraine." For reasons stated below, however, it is believed that this slight readvance of the two lobes was not simultaneous and that the eastern arm of Woodworth's Falmouth moraine can be distinguished from the part that extends southwestward paralleling Buzzards Bay. The Buzzards Bay lobe laid down its recessional moraine at the edge of the pitted plain somewhat earlier than did the Cape Cod Bay lobe, so that the Sandwich moraine overlaps and lies upon the northern end of the Buzzards Bay moraine near the Cape Cod Canal.

After the Cape Cod Bay lobe had shrunk back, spreading more outwash in its wake, north of Sandwich moraine, another episode of colder or more humid conditions drove it forward again, not so far as before, but far enough to deposit a smaller, narrower, less continuous moraine, the Scorton moraine, upon this later outwash. The Buzzards Bay lobe apparently left no easily-recognized record of similar readvance, although possibly such a record lies concealed beneath the water of Buzzards Bay or is represented by small patches of till on top of gravel between the moraine and the Bay shore.

During a later episode of retreat the ice front of the Buzzards Bay lobe receded many miles northwestward, perhaps as far as Kingston and South Duxbury before it halted. The Cape Cod Bay lobe withdrew likewise northward into the Bay. Then its southwestern margin pushed forward again and stood for a long time in a zone extending northwest from the vicinity of Ellisville toward Plymouth. Here it built a third prominent recessional moraine which is called the Ellisville moraine for the present.

The Buzzards Bay lobe had left enormous blocks of ice in what must have been a continuous valley area close to the southwest margin of the Ellisville moraine. These are now marked by the deep, elongate depressions that contain Great Herring Pond, Little Herring Pond, Bloody Pond, and Long Pond in the Sagamore quadrangle. These blocks were covered by a compound fan of outwash gravels and sands poured out southwestward from the Cape Cod Bay lobe simultaneously with its construction of the Ellisville moraine. Thus the blocks remained while another outwash plain, the Wareham pitted plain, was formed above them, and then they melted away to form huge kettle-holes below its surface. The relationship of the Wareham pitted plain to the bordering Ellisville moraine is different from the relationship of the Mashpee pitted plain to its bordering moraines. The southwestern margin of the Ellisville moraine is irregular and difficult to follow, because the gravels of the Wareham pitted plain slope up

to cover portions of it and extend into it in places. Such an irregular overlapping and interfingering of deposits is typical of the relations between a moraine and an outwash plain that are built simultaneously.

The story of the activity of these lobes as they drew back still farther to the north and west must be deferred until the quadrangles adjacent to those covered by the writers have been mapped.

The area of the Cape east of the quadrangles that have been mapped in detail is underlain in part by deposits continuous with those mentioned above. The Mashpee pitted plain extends into the Cotuit quadrangle, and the Sandwich moraine stretches eastward along the north shore of the Cape. N.E. Chute's recent study (2) substantiates the conclusions of earlier workers that another large pitted plain extends southwestward on the southeastern end of the Cape and spreads toward the Mashpee pitted plain. The eastern arm of the Cape from Chatham to Provincetown may be in part an interlobate moraine formed between the Cape Cod Bay lobe and the Massachusetts Bay lobe, but the complexities of its geology require careful study before we can outline in any detail the story of Pleistocene conditions in that area.

Wind-sculptured Stones (Ventifacts)

During both the advance and the recession of the Wisconsin ice over the Cape Cod region strong winds blew down across its irregular surface and whirled up clouds of sand and silt on the outwash plains and the exposed seafloor in front of the glacier. Sandstorms must have been frequent, and a current of wind-driven sand must have been moving close to the land surface almost constantly. Blocks and boulders and even smaller stones that lay in the path of this sand-blast were worn and polished. Smooth, almost flat surfaces were bevelled across rounded rocks. (Fig. 4a). When these stones were dislodged and rolled into new positions, other parts of them were likewise bevelled. Some of the rounded cobbles became pyramid-shaped and sharply angular where one wind-cut facet intersected another. (Fig. 4b). Even granite and quartzite pebbles, which are normally as hard as or harder than steel, were shaped by this incessant abrasion. Many of the wind-scoured stones have irregular pits and grooves or furrows where the sand stream etched out their less resistant parts. (Fig. 4c,e,f).

Some stones lay exposed to such action for a long time, and they bear marked evidences of the wind-cutting; others were quickly covered or protected by falling into the lee of larger stones or by being shifted out of the wind-blast, and they show only the beginnings of modification by sand-blasting. Some of these stones, of course, never moved out of position before they were buried by sand or by later till or outwash. They show wind-sculpturing, therefore, on but one side. Some were picked up after they had been cut and were moved to a different location by streams of meltwater or by the advancing ice itself. Consequently, they now lie embedded in till or deep within the layers of outwash gravel. During this second

transport, the smooth, shiny, wind-polished surfaces became dull, the sharp edges were rounded off (Fig. 4d), and the evidences of wind-cutting were commonly almost destroyed by another type of abrasion. The surface of such stones feels harsh and gritty, like that of any stream-borne pebble, whereas the wind-smoothed surfaces that have not been thus partially obliterated, have a greasy feeling like talcum powder."

Without particular effort nearly 2500 of these wind-cut stones were collected from all over the area considered in this report, in the midst of undisturbed gravel layers, in slumped materials along the faces of cliffs, embedded in till of the moraines, or lying on the surface. Scores more were found in similar materials in various other parts of the Cape. J.B. Woodworth (6) reported occurrences of them in areas which have not yet been re-studied. Literally millions of such stones must lie in the glacio-fluvial gravels and tills of this region. Their distribution is, however, very irregular and random. One gravel pit may yield hundreds of these stones although nearby pits reveal scarcely any, or one layer in an exposure may consist of them almost entirely whereas the rest of the layers contain none. Considering the conditions under which they were produced, this is, of course, not surprising.

N.E. Chute (2), following Kirk Bryan's (1) interpretation of these wind-worn stones or ventifacts, thought they were formed at the surface by wind action and then churned down into the subsurface materials by overturning of the upper few feet of soil during frost action. The authors do not agree entirely with that conclusion, for a great many of these rocks were obviously cut while the ice still stood nearby, were buried during its subsequent movements, and have not been disturbed since that time. It seems likely that most of the wind-sculpturing was accomplished before the ice blocks had melted to produce kettle-holes, because there is very little wind-blown sand in any of these holes. They would have been nearly or quite filled with sand if they had stood open when the wind was driving large amounts of sand across the surface of the ground. In their opinion, therefore, many of the ventifacts which now lie in the thin zone of disturbed material near the surface were already embedded in the upper part of till and gravel deposits before the disturbance by frost and other agencies ever occurred.

Recent Modification by Erosion and Deposition

Development of Gullies

Erosion of the glaciated territory by rainwash and by wind was in progress during the recession of the glacier, and newly-formed land surfaces were subject to such attack as soon as they were uncovered, or even while they were being built up in front of the ice. Wind action diminished after the ice withdrew. Vegetation spread over the Cape and prevented the sands of the outwash plains from drifting about as they must have done while the ventifacts were undergoing sculpture by sandblast. As the climate became gradually warmer and the seasons of freezing weather grew shorter, the number of rainstorms each year increased, and erosion by running water was more continuous. Many small gullies developed as the run-off began to cut down through the loose deposits. Present lines of generally poor drainage were established, a few swampy areas were drained, and the landscapes which had come into existence during the Pleistocene epoch were somewhat modified by Recent erosion. The degree of such modification, however, is so slight, considering that such loose, unconsolidated materials are subject to rapid erosion, that the time that has elapsed since the retreat of the ice could not have been very long.

Marine Submergence and Erosion

The rise of sealevel that occurred when the ice melted brought the Atlantic strandline slowly back toward its present position. As the water rose, it finally lapped against the outermost moraine. The lower parts of this were submerged, and wide stretches of it were cut away by the pounding surf. The moraine belts on Nantucket and Martha's Vineyard are the only remnant of this moraine that remain above sealevel in the Cape Cod area. Spread behind them, the sea formed Nantucket Sound and Vineyard Sound and began a similar attack on the recessional Buzzards Bay moraine at the southwest. The Elizabeth Islands represent the higher parts of this moraine southwest of Woods Hole, and the steep cliffs of till fronting the irregular shoreline in this part of the Cape are still undergoing violent attack by waves. The eastern arm of the Cape, facing the heavy storms of the open ocean, offers little resistance to the onslaught of northeasters. It has been cut back at least a mile or two in the last few thousand years, (2a) and will become continually narrower. Near Wellfleet only about a mile of land with glacial topography now separates the waters of Cape Cod Bay from those of the open ocean. Along the south shore, the sea flooded the lower ends of the long furrows in the outwash plains, turned them into narrow estuaries, and invaded large kettle-holes to form such embayments as Waquoit Bay (Falmouth quadrangle). The irregularity of the coast with its many excellent harbors for small craft is a result of this widespread drowning of the uneven, glacial landscape.

Beaches, Sandbars and Dunes

Materials derived from erosion along the coast have been distributed by waves and currents to produce fine beaches and sandbars, especially along the southern and eastern sides of the Cape. Currents moving parallel to the coast along the south shore built bars across many of the bays, improving them as harbors for small boats by affording protection from the open waters of the Sounds, and straightened the actual shoreline by thus reducing its irregularities. A similar process occurred on the north shore in the vicinity of Wellfleet. Monomoy Point and many other similar coastal features are sandbars piled even above the high-tide mark by the waves and currents. As each new bar jutting out from the coast is built, it protects certain parts of the coast from direct attack and causes further deposition of sand at some places; but it may also deflect currents and cause more vigorous erosion elsewhere. The broad hook on which Provincetown is located at the tip of the eastern arm of the Cape has been built up since the Ice Age by sand carried there from the cliffs to the south.

Wherever the beaches are wide enough to expose large quantities of loose sand to the sweep of the wind, dunes have been formed. The largest and most extensive of these are, of course, those near Provincetown and Barnstable, but along many stretches of the coast there are patches of windblown sand lying against the cliffs on the inner margin of the beaches.

Changes in the Surface Zones

The upper few feet of till and gravel deposits have been altered by several agencies since the retreat of the ice sheets. Frost has heaved and overturned some of the stones. Roots have penetrated between them and shifted them. In the upper two or three feet at any exposure, all signs of original layering in outwash materials have been destroyed. The topmost six inches to a foot generally consists of chocolate brown to black, sandy soil, rich in plant remains. Beneath this is a reddish-brown zone in which the subsurface materials have been stained with iron rust that comes from decay of iron-bearing minerals in the soil and is spread by the downward percolation of rain water through the ground. Generally the lower part of the rusty zone grades downward into a lighter colored zone, of yellowish brown or tan color. Thus, the bottom of this stained zone is very irregular, and its contact with unstained materials below is commonly rather indistinct. The rusty stain locally penetrates to deeper levels in more porous materials or along irregular cracks. Commonly it is hard to tell at any single roadcut or pit just how much of the upper disturbed and weathered material was churned up and altered in place, and how much material has been brought there and deposited as a thin top mantle by slope wash and creep from adjacent hills. Regardless of its origin, however, the thinness of the zone of disturbed material corroborates the conclusion that not a great deal of time has elapsed since the ice disappeared from this region.

At many places, especially in areas covered by pine trees, there is a thin zone of white sand immediately beneath the surface of the ground, ranging from less than an inch to three or four inches in thickness. This is a result of the removal of vegetal humus and iron oxides by a process of leaching that seems to be especially effective under the conditions that obtain where pines are abundant. This bleached zone may be developed in the soil formed on till or glacio-fluvial materials alike, and its presence or absence is determined by the chemical composition of the rainwater seeping into the ground at the present time. This varies more from place to place because of the considerable differences in vegetation than because of the less significant differences in the mineral content of the various kinds of glacial drift.

Swamps and Bogs

With the return of vegetation to this area, salt marshes developed close to the coast where sandbars had formed lagoons by enclosing embayments in the coastline, and the inland ponds and swamps were densely populated with plants of many types. These flourished and died, and new generations grew upon one another repeatedly, so that salt-water peat was formed in the lower districts and fresh-water peat in inland hollows. Many of the smaller ponds in kettle-holes have been completely filled with peat accumulated during the centuries of Recent time. In places this mat of vegetal tissue is more than 12 feet thick. During the hurricane of 1938 waves broke across sandbars at some localities and plunged into such peat accumulations. Great mattresses of peat several feet thick were loosened, carried out on the receding waves, dashed to thousands of fragments by the surf. These were then spread along the beaches for miles from their source. Along certain short stretches of the coast, shoreline erosion has cut back through the material on one side of a modern peat bog and is now removing the peat.

Origin of the Landforms of Western Cape Cod

Mashpee pitted plain

Location, Size and Shape

More than 100 square miles of surface at the west end of Cape Cod in the Pocasset, Falmouth, Sandwich, Cotuit and Hyannis quadrangles,/ are underlain by loose, stratified sand and gravel. This material is exposed in scores of small pits excavated around cranberry bogs and along closely-spaced roads. At many places the surface of the sand and gravel forms a nearly flat plain, as at the Massachusetts National Guard Camp, located in the southeastern corner of the Pocasset quadrangle (Plate II). Other extensive portions of the surface are naturally pitted (as explained farther on under the heading "evidences of buried ice") and undulating. Long furrows also break the smoothness of the plain, and even its smoothest portions have a systematic gentle slope toward the south or southeast. These features suggest a long and complicated history. The name of the plain is derived from the town of Mashpee.

Originally, it is thought, this was a continuous, smooth plain without either pits or furrows. It is fan-shaped and the small end or apex lies in the right angle formed where the Sandwich moraine overlaps the Buzzards Bay moraine. The outer edge of the fan now lies partly submerged beneath the waters of Nantucket and Vineyard Sounds. The present shoreline across this outer edge forms a broad convex curve from Falmouth to Cotuit.

The surface of the fan slopes gently but regularly from the apex, 220 feet above sealevel, south and east to the outer edge which is just below sealevel. This surface slope is very slightly concave upward, for it is distinctly steeper near the apex of the fan than toward its periphery. (Fig. 5). In the higher half of the plain, within six miles of the apex, the average slope is 15 to 20 .16-.22 feet per mile. Broad depressions formed near the apex at a later time suggest that the original slope of deposition before pits were made may have been even greater. Indeed, some non-pitted portions of this upper part of the plain drop as much as 25 feet in one mile. 0.27° The lower half of the plain, on the other hand, has a surface slope of only 12 to 15 feet per mile where it is not pitted.

0.13° - 0.16°

Origin of the Plain

Many of the features of this gravel plain resemble closely those of the deposits being made today by streams that issue from beneath the Greenland and Iceland ice caps. Such streams of meltwater are loaded to capacity much of the time with rock fragments from the ice. This debris literally chokes the channels of the streams, forcing

/Of the quadrangles named only the Sandwich has been published and is available for distribution by the Geological Survey.

their waters to divide and redivide into many smaller streams, each of whose channels also finally becomes clogged so that new ones are continually being formed. Such channels are cut during and just after warm hours of the day when floods of meltwater issue from the ice. The channels become filled and blocked with debris during the receding of the waters at night or in cold periods when currents are less swift. Thus these manifold streams form a braided pattern constantly shifting over the plain. In this way, first one and then another part of the broad plain is built up.

Since the meltwater is often fed from one fixed outlet in the glacier, or from between the ice edge and a nearby mountain wall, the deposit gradually assumes a fan shape radiating from that source. The constructional surface of this fan slopes away from the apex and tends to be concave, for the coarser materials near the apex build to a steeper angle than the fine material washed toward the outer edge.

One would expect that the largest boulders, cobbles, or pebbles rolled by the periodic floods would be transported the shortest distances. They would come to rest before sand would settle. The distribution of material in the Mashpee pitted plain bears out this principle. The average size of the particles composing the plain changes distinctly from that of well rounded gravel near the apex to subangular sand at the outer margin. In the apex, rounded boulders 6 to 24 inches in diameter are scattered over the surface. One pit in this apex located near the Pocasset Road, 1000 feet north of its intersection with Jefferson Road (Plate II), shows 4 to 6 feet of very coarse gravel overlying 3 feet of cross-bedded sand with thin gravel lenses; a trench in the Military Reservation north of Snake Pond exhibits coarse gravel. Many shallow road cuts show the general presence of gravel in this part of the plain. On the other hand, exposures in the wave-cut cliffs of the outer, seaward edge of the plain consist almost exclusively of sand. Pits excavated for sand used in surfacing roads and bogs are scattered along State highway, Route 28, and around each cranberry bog in this vicinity. Very little coarse gravel is available in these pits.

There are exceptions to this gradation in coarseness, however. Most notable is a pit operated by the Lawrence Co. and located just west of Sols Pond, $1\frac{1}{2}$ miles northwest of Falmouth Heights. Although this locality is only a mile and a half from the southern edge of the plain, it shows a 6-foot layer of extremely coarse gravel containing rounded boulders up to 18 inches in diameter. On the floor of the pit are a few boulders as much as 30 inches long. Similar coarse gravel with rounded cobbles 8 inches in diameter occurs in a nearby pit just southwest of Teaticket Village. The eastward dip or slope of the layers and of the surface between pits in this vicinity suggests that this unusually coarse material was deposited by meltwater that issued from the adjacent Buzzards Bay lobe while the Buzzards Bay moraine was under construction. Apparently streams from that source built a small local fan on top of the more extensive and older deposits of the Mashpee pitted plain at this place.

The layering or bedding of the sand and gravel composing the plain resulted from alternate periods of flood and slack water in the streams. Abrupt changes in grain size distinguish adjacent layers in all pits;in places a coarse gravel bed rests upon a fine sand bed, and vice versa. The power of the currents which deposited these beds was unusually variable. Even within a single bed of sand, current action has resulted in criss-cross patterns of the fine layers known as cross-bedding. Groups of fine, light and dark, laminae of sand slope in many directions. Such cross-bedding was best exposed in 1939 in a pit along State highway, Route 28, at the head of Great Pond. In coarse gravel, the "scour and fill" nature of the deposit is evident. On the southwest wall of the Lawrence Company pit referred to above and in numerous gravel pits in higher parts of the plain, some of the gravel layers fill broad hollows shaped like lenses.

Lensed bedding

All of the thicker beds, whether they are extensive or not, are essentially parallel to the surface of the plain; none is inclined steeply forward in the direction of stream flow. Such "foreset" structure would be indicative of a delta built by streams in a body of standing water. Lack of any such structure here, even in pits at the outermost edge of the exposed plain, indicates that this fan was built on land, and not to accord with any lake surface or sealevel.

Evidences of Buried Ice

The tremendous natural pits in the plain are most convincing evidence that this is glacial outwash. These pits occur chiefly in groups near Falmouth, Coonamessett, Massachusetts National Guard Rifle Range, Forestdale, Farmersville, Newtown, the vicinity of Johns Pond, Waquoit, and Osterville. There is no system or regularity to the grouping or to the positions of groups of pits in the plain. More than 30 pits exceed half a mile in length. They range in depth from 50 to 120 feet, and several are enclosed completely by gravel walls to such depths. The most prominent examples are the depression which contains Snake Pond west of Forestdale and the hollows in the Massachusetts Guard Rifle Ranges near the center of the Pocasset quadrangle. About 500 smaller pits are shown as depression contours on the new topographic maps of the Geological Survey, and many others observed in the area under discussion are too small to show on maps of the scale used. The side slopes of the pits are inclined at angles ranging from 5 to 20°. Slopes around adjacent depression centers coalesce to form saddle-shaped ridges. The pits vary greatly in shape; some are nearly circular, some elongate oval, and some quite irregular. Within an area of compound pits, the surface may resemble the hummocks and hollows of small "kame and kettle" deposits so common in the valleys throughout New England.

These features -- the irregular grouping, the great depth, steep slopes, and irregular shape -- are prime characteristics of glacial kettle-holes. Such depressions were produced when masses of ice, separated from the main ice sheet, were surrounded and partially or completely covered by accumulating outwash gravel. Some years or

centuries later these ice blocks melted away, the protective cover of gravel and sand collapsed into the holes where the ice had been, and the unconsolidated material banked against the sides of the ice gradually slumped toward the bottoms of the cavities. Neither river action which produces long and narrow or lens-shaped hollows, nor wind action which makes a broad shallow blowout, nor frost action which subdues and fills deep holes is a satisfactory explanation for pits with such shape and distribution. Furthermore, several of them, such as those occupied by Long Pond and Oyster Pond near Falmouth, or one lying southeast of Signal Hill in Sandwich, extend from within the plain to within the bordering superficial glacial moraines. As these hollows interrupt the continuous front of the moraine, they must have formed after the moraine was built on top of the margins of the outwash plain by readvancing ice. Clearly then these are holes resulting from the melting of ice which had been buried during the deposition of the plain.

Source of the Materials

Two other conditions point to the fact that this plain consists of glacial outwash. The head of the plain lies at an altitude of more than 200 feet, which is far above any ordinary stream course of the recent past. River deposits at this altitude could have formed only if there had been glacial ice to support the loaded channel of a stream at this high level. Secondly, fragments of rock of the types known to crop out as solid ledges many miles to the north and west of the plain are abundant among the pebbles in the gravel of the plain. Pebbles of Squantum tillite were found at Falmouth Heights and in a pit west of Coonamessett River, northeast of Round Pond. Carboniferous conglomerate pebbles from the Boston or Narragansett Basins were found at a dozen or more exposures. Gray-green melaphyr pebbles like those of the Boston region may be found at several localities. The scarcity of these types suggests that they are the few pieces that travelled 25 to 60 miles from their sources and became mixed with far more abundant stones from nearer sources. Varieties of rock like the Dedham granodiorite, which make up a large part of every pebble count, probably came from buried ledges of bedrock only a few miles away, although no actual ledges are visible within 10 miles of the plain. Regardless of the distance they may have travelled, the only plausible sources for these types of rock are north or west of Cape Cod. Southward or eastward transportation by moving ice and its associated meltwater is implied by their presence in the deposits described here.

Marginal Areas

As already stated, the Buzzards Bay and Sandwich moraines, which are belts of glacial till deposited directly from the ice itself, were laid on top of stream-washed sand and gravel at the western and northern margins of the pitted plain. This underlying gravel is in all respects like the gravel of the pitted plain, but its surface is

50 to 100 feet lower than that of the plain. Presumably, this gravel is continuous with that of the plain. As may be seen along the western side of the Buzzards Bay moraine, its surface beneath the till is not smooth like so much of the plain, however, and great angular blocks are embedded in it here and there. Therefore, it is believed that these portions of the plain, now buried under the moraine, were originally the marginal portions of the great fan as it was constructed during retreat of the ice before readvance produced the overlying moraine. Such portions were deposited on and around irregular masses of ice at the ragged edge of the ice sheet. Shifting currents, such as would result from movements of water over this rough and changing landscape, deposited layers sloping at unsystematic angles. The irregularity of the surface increased as the buried ice melted. Angular blocks from the ice fell and slid onto the gravel at some places.

Source of the Meltwaters

The water which built the pitted plain carried some fragments of rock like those found in both the Sandwich moraine on the north and the Buzzards Bay moraine on the west. Counts of the number of different kinds of rocks among 200 pebbles selected at random at each of 12 locations bear out this subjective observation made at innumerable pits (Table 2a). Only one stone count, that from a pit west of Peters Pond in Forestdale near the southwestern corner of the Sandwich quadrangle, is closely similar to counts in the Sandwich moraine, and only two stone counts, one made west of the Massachusetts National Guard camp on Turpentine Road near the center of the Pocasset quadrangle, the other almost half a mile east of Shallow Pond on the north side of Mill Road in the northwestern part of the Falmouth quadrangle, are much like counts in the Buzzards Bay moraine. The average of all pebble counts from the plain shows a proportion of granites, diorites, and basalts like that of the Buzzards Bay moraine, whereas the proportion of volcanic and quartzite pebbles is like that of the Sandwich moraine. Because the proportions of several types of rock contained in the two moraines are significantly different, as may be seen in Table 2b, it is concluded that the water that bore gravel to the pitted plain gathered material from sources under both lobes of the ice sheet. During transportation these pebbles were fairly well commingled.

The uniform slope of the plain to the south and southeast, away from the apex and in directions parallel to each moraine front, shows that a considerable part of the water entered the plain somewhere near or at the present apex, rather than here and there along the line of the moraines. At two localities, one located half a mile southeast of Signal Hill and about a mile northwest of the center of the Pocasset quadrangle and the other just north of Falmouth near Grews Pond, the plain shows a marked slope away from the bordering moraine. In the first of these the deposit is made of sand and is shaped like a small fan. At the Falmouth locality it is made of coarse gravel already described in discussion of the Lawrence

Company's pit. Presumably, water that flowed through breaks in the ridge on the east side of the Buzzards Bay moraine or directly from the face of the Buzzards Bay glacial lobe superimposed fans on top of the main plain at these two localities.

Associated Older Gravels

At two other places constructional gravel deposits rise above the general surface of the pitted plain. The most conspicuous one is Falmouth Heights on the shore of Vineyard Sound. The present shape of the deposit is elliptical, and its top is 35 feet above the adjacent plain. On the seaward side a 40-foot wave-cut cliff consists entirely of crossbedded sand and gravel. In the upper layers of the gravel are many ventifacts. This gravel must have been deposited as outwash from the ice prior to the building of the pitted plain, for its altitude implies ice or other gravel immediately surrounding the present site to enable streams to deposit at such a high level. This deposition occurred before any other event registered by the surface deposits on this end of Cape Cod. Presumably it occurred while the ice front was retreating from Martha's Vineyard toward the line of the Buzzards Bay and Sandwich moraines. Originally the deposit may have been far more extensive. If so,most of it must have been removed, in part by streams from the ice that was retreating north and west of it long before the low outwash fan was built around it and in part by ocean waves which are now active at present sealevel.

It is more than likely that this body of gravel never extended very much farther toward the north than it does today, and that it represents the apex of an outwash fan built southward from an ice front that was temporarily standing close by the Heights. Rather rapid recession of the ice then removed the support from the north side of the fan, and subsequent outwash deposits were never built to so great an altitude.

The other outwash deposit above the pitted plain is a discontinuous, broad, low ridge trending southeast from the edge of the Sandwich moraine north of the Cape Cod Airport into the plain as far as the Barnstable-Falmouth Road. At its northwest end, this ridge blends into the moraine front;at its southeast end it is half a mile south of the moraine. Its undulating crest rises 10 to 25 feet above the adjacent plain, and it consists of well-bedded and crossbedded sandy gravel without boulders. The gentle south slope and slightly steeper north side of the ridge suggest that it, too, was deposited by glacially-fed streams when the ice edge stood close to or along its northern margin.

Till Clumps in Gravel

Till is not ordinarily found in glacial outwash. Till comes directly from ice; gravel is washed and sorted by the meltwater. Irregular clumps of till were found, however, in excavations at six localities in the Mashpee pitted plain in the midst of gravel far

Stonecount Data

Mather, Goldthwait and Thiesmeyer
Table 2a

LITHOLOGY OF PEBBLES IN THE MASHPEE PITTED PLAIN ON CAPE COD

Locality:	T-105	G-95	G-59	G-47	G-12	G-40	T-35	G-61	G-81	G-65	T-79	G-35	AVERAGES: MASHPEE PITTED PLAIN	BUZZARDS BAY MORAINE	SANDWICH MORAINE	AREA OF OVERLAP OF MORAINES
Localities designated T represent collections by Thiesmeyer; G.Goldthwait	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
GRANITE (including gneissoid granite, aplite, pegmatite)	61	59	71	62	67	70	71	76	75	47	68	72	67	66	45	60
QUARTZ-FELDSPAR GNEISS	5	2	0	0	0	0	0	0	0	1	0	2	1	1	3	0
DIORITE and GABBRO (including biotite gneiss)	3	3	2	6	6	2	0	0	1	5	1	2	2.5	3	3.5	2
BASALT (including basalt-porphyry)	7	4	1	5	0	6	2	2	1	15	3	2	4	3	9.5	5
OTHER VOLCANICS (mostly rhyolite and pyroclastics)	9	17	6	9	8	4	10	7	11	11	5	6	8.5	4	13.5	11
SCHIST (including greenstone)	5	2	3	2	7	2	0	1	0	3	7	2	3	3	5	4.5
SLATE (including argillite)	2	2	2	1	0	1	0	0	1	0	0	0	1	t	4	2
QUARTZITE	5	5	7	8	2	6	7	7	5	7	9	7	6	11	7.5	9
VEIN QUARTZ	3	7	7	6	9	9	9	6	5	9	6	6	7	8	7	6.5
ARKOSE and SANDSTONE	0	1	0	0	0	0	0	0	0	1	0	0	t	0	1	t
CONGLOMERATE	0	0	0	0	0	0	0	1	1	0	0	0	t	t	0	0
UNIDENTIFIED	1	0	1	2	1	0	1	0	1	1	1	1	1	1	1	1

East to West   North   to   South

Stonecount Data

LITHOLOGY OF PEBBLES IN CAPE COD MORAINES

	BUZZARDS BAY MORAINE								SANDWICH MORAINE							AREA OF OVERLAP				
Locality:	G-80	G-79	G-33	G-38	G-78	G-14	G-82	Average	G-55	G-42*	T-80*	G-98	T-82*	T-83*	Average	T-67	T-124	T-121	T-122	Average
Localities designated G represent collections by Goldthwait; T.Thiesmeyer	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
GRANITE (including gneissoid granite, aplite, pegmatite)	69	72	70	67	61	66	58	66	55	36	38	35	57	50	45	56	56	71	58	60
QUARTZ-FELDSPAR GNEISS	0	6	0	1	0	0	0	1	0	5	2	4	5	3	3	0	0	0	0	0
DIORITE and GABBRO (including biotite gneiss)	3	1	0	0	9	9	2	3	4	4	7	3	1	2	3.5	1	4	0	3	2
BASALT (including basalt-porphyry)	3	2	3	2	3	4	3	3	4	11	11	13	5	13	9.5	6	6	5	3	5
OTHER VOLCANICS (mostly rhyolite and pyroclastics)	2	2	0	0	0	5	0	4	10	18	16	19	9	10	13.8	15	11	5	12	11
SCHIST (including greenstone)	7	7	0	3	1	1	2	3	0	3	4	5	9	9	6	3	3	7	5	4.5
SLATE (including argillite)	0	0	0	1	0	0	0	t	2	3	7	4	3	6	4	0	4	2	2	2
QUARTZITE	12	6	18	12	15	5	11	11	14	5	10	10	4	2	7.5	9	8	6	14	9
VEIN QUARTZ	5	4	9	8	6	7	16	8	11	11	4	6	6	6	7	7	9	6	4	6.5
ARKOSE and SANDSTONE	0	0	0	0	0	0	0	0	0	3	1	2	0	0	1	1	0	0	0	t
CONGLOMERATE	1	0	0	0	0	0	1	t	0	0	0	0	0	0	0	0	0	0	0	0
UNIDENTIFIED	0	1	0	1	0	3	1	1	1	3	2	0	1	0	1	2	0	0	1	1
	Southwest		to		Northeast				West		to		East							

out on the outwash fan. These are 1) a pit half a mile east of Handys Ponds in the south-central part of the Pocasset quadrangle, 2) a pit almost two miles northeast of this on Bear Hollow Farm south of Snake Pond, 3) a pit one and a quarter miles northwest of Bear Hollow Farm (poorly exposed), 4) a pit three-fourths of a mile west of Bear Hollow Farm and a mile north of the Military Reservation, 5) several excavations near a cranberry bog about half a mile southeast of Teaticket Village in the west-central part of the Falmouth quadrangle, and 6) a roadcut at the north end of Pimlico Pond at the southwestern edge of the Sandwich quadrangle. (See Plates I and II). Similar clumps were noted in a pitted plain that extends across the Sagamore and Wareham quadrangles west of the Cape Cod Canal. Each of the six localities is at the rim or edge of one of the many kettle-holes. No clumps were found in the hundreds of pits along roads elsewhere on the smooth parts of the plain or in small pits around cranberry bogs that have been developed in the furrows. From this restricted association it is concluded that this till was once associated with the isolated ice masses responsible for the kettle-holes.

That these clumps are composed of till is established by the following characteristics:

1. Fresh rock flour in the matrix.
2. Abundance of silt and fine sand particles which retain moisture after surrounding gravel has dried.
3. Angular and subangular rock fragments up to one half a foot in length at two exposures; smaller at the others.
4. Varieties of the rock fragments, all of which are rock types found in the Buzzards Bay moraine to the west.
5. Lack of sorting by water, or bedding, in any clump.
6. Compactness and coherence such that clumps stand out after the surrounding sand is removed.

At each locality from one to ten such clumps were found. Each one is stained by a bright red rim of iron oxides, 2 to 8 inches deep, and streaks of similar composition that pass through the center of the clump. The gravel immediately adjacent is similarly stained. All of the clumps yet discovered occur in the uppermost 6 to 8 feet of the gravel plain, and some of them reach to the ground surface. Above the clumps no good bedding is evident because overturning and mixing by roots, frost, and animals to a depth of about one foot obscure all possible structure. Below the clumps in each instance there is bedded gravel and sand. The filling between clumps is relatively loose, non-bedded sand and fine gravel.

As the clumps are at the top of sand and gravel of unknown thickness, they must have come into position late in the building of the plain. For several reasons it is believed horizontal pressure was exerted on the till clumps as they assumed their present positions. The uppermost beds of gravel beneath the clumps appear vaguely wrinkled into wave-like crests in the spaces 1 to 4 feet wide between the bases of adjacent clumps. At the Teaticket locality the long till clumps stand on end (Fig. 6). Near Bear Hollow Farm the long axes of clumps are all inclined in the same direction. At the National Guard locality, where the till masses lie more or less

horizontally, the ends of many masses are twisted into a scroll-like form. The horizontal pressure which accomplished these feats must have been exerted at or near the surface of the plain, for gravel layers several feet below the clumps are undisturbed.

Such pressure may have resulted from the expansion of the ice at the top of a stranded ice block. Here the ice is in contact with rapidly-fluctuating air temperatures. If the ice is warmed from a temperature far below freezing to freezing, it spreads outward. Another possible explanation is that streams on the outwash plain undercut the edges of these ice blocks, causing large masses of ice to fall and be dragged short distances in a stream channel. Chunks of till from the ice might drop directly onto the gravel floor and become squeezed into place under this ice.

Subaerial Furrows

The surface of the Mashpee pitted plain is scored today not only by kettle-holes, but also by long furrows which head about midway up the plain and extend to its outer edge. The longest is about 10 miles long. The lower parts of the larger furrows are now drained by small streams such as Coonamessett River and Childs River in the Falmouth quadrangle, but these rivers are not actively enlarging the furrows today. The lower end of each is flooded by the sea, which has thus formed such long, narrow bays as Great Pond, Green Pond, Bowens Pond, and Eel River on the south shore east of Falmouth.

Erosion rather than deposition is responsible for these furrows, inasmuch as they are actually cut into the sand and gravel layers of the plain. The truncated edges of gravel beds may be seen in exposures on the walls of furrows. Two of the best exposures were seen in 1939 in roadcuts a quarter of a mile southeast of Jenkins Pond and a quarter of a mile southeast of Round Pond. Furthermore, the furrows have the form of stream-cut valleys. Each one heads in a narrow, shallow, V-shaped cut. Down valley, most of these furrows increase to 1,000 feet in width and some 25 feet in depth. The floors of the furrows are broad and smooth. Short V-shaped tributaries enter the main valleys along their sides, giving each system a stunted dendritic pattern like the veins of a narrow leaf.

The close spacing of the furrows and subparallel orientation of all their main courses are surprising. Some adjacent furrows are so close where they enter Nantucket and Vineyard Sounds that the flat-topped remnants between them are rarely as much as one half a mile broad. All of them are oriented within 20° of south, some trending southeast and others southwest. Those near the western edge of the plain are nearly parallel to the Buzzards Bay moraine. Such an arrangement of valleys is not like the dendritic "crows-foot" pattern formed by so many streams in New England, and it, therefore, requires some special explanation.

What sort of erosion might carve such valleys? As many furrows are not now occupied by streams, present-day erosion is totally inadequate to account for these forms. As the headwaters are not directly connected with moraine areas, and as the pattern of the furrows

is not a braided one, dividing and rejoining, as among overloaded streams, they were not cut by the same streams of glacial meltwater that once constructed the plain. It has been suggested that after the plain was essentially complete, the extra supply of water from ice melting west and north of the moraines saturated the loose gravels. This ground water might have reached the surface as springs part way down the fan and flowed on the surface from there to the sea. A second possibility is that there was a period of barren, treeless climate, caused either by drouth or cold, during which ephemeral rains cut shallow channels in the gravels. Another suggestion is that the existence of frozen ground, generated by the rigorous cold conditions while the ice sheet still covered the interior of New England, made all except surface gravels impermeable to water, and induced shallow cutting in closely-spaced channels.

Persistence of Buried Ice

The duration of all the events that contributed to the shaping of the present Mashpee pitted plain is very impressive. The first event was the separation of large masses of stagnant ice from the wasting ice sheet. Then, braided streams of meltwater deposited sand and gravel, layer upon layer, around and over many of those bodies of ice before they melted away. The period required for the construction of such a large plain, which now contains more than two cubic miles of gravel, must be estimated in many tens and perhaps hundreds of years.

In the surface of the plain there are many thousands of stones which were plainly cut, grooved and faceted by the wind. These may be found singly or in quantity in nearly half of the pits now excavated in the plain. The deep etching of these ventifacts and their abundance impress all who see them with the vigor and duration of the wind action that must have been responsible for them. No comparable wind action takes place on most of the Cape today. Many of these ancient ventifacts are actually in the beds of gravel near the surface of the plain, but they could not have rolled far in the streams which built that portion of the plain or the delicate polish and edges made by the wind would have been obliterated. It is necessary, then, to infer that the completion of even the upper layers of the plain took many tens and perhaps hundreds of years during which wind action was very intense.

Buried ice persisted under the sand and gravel of the plain all the time that wind was so active, for none of the sand or silt that must have been blown by the wind as tools for the sandblast is found filling the kettle-holes. Furthermore, the furrows were cut before the ice entirely disappeared. Furrows are found to enter and exit from groups of kettle-holes with no change of direction. There is no sign that drainage was from one kettle-hole to another. Dozens of small pits occur on the floors of furrows, and in some places large pits interrupt and separate a whole headward section of furrow from its lower flooded end at the sea. Had these low kettle-hole depressions existed when the furrows were cut, they would certainly

have been filled with stream gravel to the level of the channel floor. As this is not true, it is inferred that the blocks of ice remained not only until the plain was built but also until the furrows had been cut.

Moreover, some of the buried ice was present when the adjacent moraines were superimposed upon the edges of the plain. Thin active ice moved forward over this gravel and deposited till without destroying the layers of gravel beneath. Masses of decaying ice caught under the first outwash gravel remained until the active ice overrode them, inasmuch as certain large kettle-holes already described (Page 23) extend from the exposed surface of the fan into the moraine-covered area. The ice finally melted away after both the gravel of the fan and the till of the moraine had been deposited.

If, then, ice lasted many tens or a few hundreds of years while the plain was being built, a few hundreds of years while ventifacts were being cut, and perhaps many score years while the furrows were being eroded and moraines were being superimposed, it may be stated with confidence that this buried ice persisted at least for several centuries. It is probable that vegetation had gained a foothold on Cape Cod long before the last buried ice had melted or evaporated.

Effect of Rising Sealevel

The final event that affected the present aspect of the Mashpee pitted plain was the drowning by the sea. At no time since completion of the plain has sealevel been higher on this portion of Cape Cod than it is today, for no sandbars were found above the modern shoreline. These would certainly be present had wave action once been higher on such a sandy shore. Moreover, none of the kettle-holes at the lower edge of the plain are filled by wave wash. On the other hand, submerged stumps of cedar trees have been dredged from below low tide level at Witchmere Harbor in Harwichport, 15 miles east of this pitted plain (2, Page 25), and at Centerville (4a) near its eastern edge. The lower end of each furrow is clearly drowned, and no process of shore erosion or construction could produce such a deeply indented shoreline. Sometime within the last 10,000 years the sea rose to its present stand with respect to all this section of Cape Cod, and sandbars were built across many of the bays and estuaries.

Ground water, which saturates the sand and gravel under the plain, rises to a height somewhat above sealevel. In the higher northwest portion of the fan only the pits 80 or more feet deep are low enough to contain open lakes. Along the lower southeast edge even some of the shallow pits 10 to 20 feet deep contain water. These indicate the uppermost level of ground water, because the top of the saturated zone in gravel can stand but little higher or lower than the surface of open lakes in depressions. For never-failing water supply, all wells must be sunk to this level. Four miles from the apex of the fan this water table is about 60 feet above sealevel. It drops systematically southward until, 10 to 12 miles from the apex of the fan, it coincides with sealevel. It slopes more gently than

the surface below which it lies. Therefore, wells will vary in depth from 80 feet in the higher, flat parts of the plain to 15 or 20 feet near the lower edge.

Low, wave-cut cliffs facing narrow sea beaches have been eroded along the low margin of the plain. If the original gentle surface of the plain be projected out in imagination beyond the present cliffs until it touches sealevel, it appears that the plain once extended from a quarter to half a mile farther seaward. Waves and shore currents have beaten the shoreline back by this amount. At distances greater than half a mile off the Falmouth shore today, or one mile off the shore at Cotuit, the Coast and Geodetic Survey charts (No. 1209 especially) show a drop-off that is far too abrupt to be continuous with the original surface of the pitted plain. If the pitted plain once extended beyond that line, recent excavation by currents, or wave cutting at some lower stand of the sea, has modified the bottom contour too much to allow reconstruction of the original outer edge of the plain.

Buzzards Bay Moraine

Location, Boundaries and Character

The Buzzards Bay moraine is a belt, half a mile to a mile and a half wide, of boulder-strewn hills and dales, knobs and hollows. It extends in almost a straight line from the north-central part of the Pocasset quadrangle southwestward across the northwest corner of the Falmouth quadrangle to Woods Hole, near the southeast corner of the Woods Hole quadrangle, (Plate I). Thence it curves westward to include the Elizabeth Islands. This is the southwestern part of Woodworth's (7) "Falmouth moraine." Its northern end terminates rather abruptly in a ragged, cliff-like edge about 100 feet high that trends almost due east and west, about a mile and a half southeast of the south end of the Bourne Bridge over the Cape Cod Canal. This slope marks a place where the ice of the Cape Cod Bay lobe rode forward over the northern extent of the Buzzards Bay moraine and pushed materials of the latter up into a hummocky ridge. When the ice retreated away from this ridge, the material slumped to form the steep slope facing northward.

Many of the irregular hills in the northern part of the moraine rise to altitudes of 250 to 300 feet above sealevel; the highest, Signal Hill, is 306 feet above the waters of Buzzards Bay. The bottoms of many of the undrained hollows scattered haphazardly among these hills are at altitudes of only 130 to 160 feet. Southwestward the general altitude of the higher knobs decreases, but the differences in altitude between the knobs and the kettle-hole bottoms are approximately the same as in the northern stretches of the moraine. In other words, the topography of the southern end of the moraine on the Cape is just as rough as it is in the Bourne area, although the general surface is nearer sealevel.

Throughout its entire length the moraine is liberally sprinkled with huge boulders and subangular blocks of rock, some of them as

much as 18 or 20 feet in longest diameter. Hardly a five-acre patch lacks an erratic that is not at least 6 feet across. This is in sharp contrast to the almost boulder-free surface of the Mashpee pitted plain. In general the boulders are distributed more thickly near the eastern margin of the moraine. This, of course, serves to intensify the contrast noticed when one crosses the rough, bouldery topography of the moraine to the smoother, almost boulderless ground of the outwash plain. The presence of so many large blocks, many of which are granite similar to the bedrock many miles to the north and northwest of the Cape, is eloquent testimony to the transporting power of the ice that brought them.

On the east the moraine is marked by a prominent, discontinuous ridge of till 20 to 60 feet high, heavily loaded with boulders, which overlooks the gently-sloping surface of the Mashpee pitted plain. This ridge or moraine-front can be seen best from a point on the outwash plain about three quarters of a mile southeast of Signal Hill and about a mile north of the center of the Pocasset quadrangle. Very few of the boulders perched on top of this ridge have been moved out and down the slopes to the east by frost action or slumping. The western side of the moraine has a much less definite, more irregular margin. The continuous till mass that makes up most of the higher ground seems to be delimited by an irregular "line" which ranges from about 50 to 110 feet above Buzzards Bay in the Pocasset and Falmouth quadrangles. West of this there are only isolated patches of till, some of which overlie sand and gravel. These are not included as part of the moraine, but are interpreted as local masses of till deposited by the ice during its retreat from the moraine westward across what is now Buzzards Bay. East of the line there is an almost continuous concentration of blocks. West of it the blocks occur in scattered patches, some embedded individually in the fine gravels that underlie this strip of lower ground, others lying on the surface either as isolated units or in clusters. At each of the pits excavated along this line one can observe sandy till that contains boulders and lies on top of distinctly-layered sand and gravel like that of the pitted plain. This confirms the conclusion that the moraine was deposited by ice which readvanced and moved forward over outwash gravels. The western boundary of the moraine crosses the State highway, Route 28, at several places between the area east of Pocasset and West Falmouth. Southwestward the boundary descends gradually to lower elevations and presumably disappears below sealevel in the Woods Hole quadrangle where the waves of Buzzards Bay are now cutting cliffs in the till of the moraine.

At some places along the western side of the moraine, however, there is no such definite boundary. Instead, a conspicuous morainic landscape merges with the main till-covered area on the east, and extends west of it over an irregular zone that varies in width up to a mile or more. Such a zone may be seen in the area between the intersection of the Pocasset-Forestdale Road with highway 28 and the crest of the morainic belt east of this. Numerous pits and roadcuts in this vicinity show that the zone is underlain by irregularly stratified sand and gravel which contains scores of large angular blocks.

These litter its surface almost as abundantly as do the blocks in the till areas. Such a zone is here interpreted as a gravelly, kame-like part of the moraine, formed where large volumes of outwash accumulated in temporary pools and hollows that stood between the receding edge of the glacier and the till moraine on the east. The large blocks and irregular bedding indicate that the ice stood nearby when they were deposited. They may have slid or rolled off the melting glacier, or they may have been rafted out over the water, embedded in or lying on cakes of ice that broke off periodically. Masses of stagnant ice weighted down with debris probably lay beneath these small lakes. When these masses melted, the surface became an area of kettle-holes and irregular hills of outwash. As this area is essentially like the rest of the moraine topographically and was formed at almost the same time, this and similar zones should be included in the Buzzards Bay moraine. Therefore, the western boundary of such parts of the moraine was placed at points where the concentration of boulders diminishes notably and the landscape is more regular.

Excepting the conspicuous blocks and boulders, the materials composing the Buzzards Bay moraine are almost completely concealed by a dense growth of grass, shrubbery, and trees. Exposures in roadcuts are common, however, especially where a network of new roads has been built through the Military Reservation of the Massachusetts National Guard east of Pocasset. The moraine in this vicinity is also marked with shallow pits where boulders were blasted to secure rock fragments for local construction projects. Cliffs cut into the till along the east shore of Buzzards Bay in the vicinity of Woods Hole provide additional opportunities to examine the nature of the materials in the southwestern part of the moraine.

Most of the moraine is, of course, made of till. Its thickness varies considerably from place to place. Many of the depressions on the rough surface are probably irregular hollows where the thickness of glacial debris is less than that composing the surrounding hills. In some roadcuts a 14-foot thickness of till is exposed. At some places along the shore, cliffs 30 feet high have been cut entirely in till, and the beaches in front of them are littered with angular blocks of rock derived from the cliffs. In fact, any boulder-strewn beach such as that from Hamlin Point southward to Woods Hole generally indicates that the neighboring cliffs are made of till.

Sandy Nature of the Till

The abundance of pine trees on the moraine would lead one to suspect that the underlying material is rather sandy, and this deduction is confirmed by hundreds of exposures. In fact, the till contains more sand or silt and less clay and rock flour than is commonly present in till elsewhere. This may be attributed to several causes:

1. The bedrock of a large part of New England over which the ice traveled is generally resistant and did not yield such large quantities of weathered material as did the limestones and shales of the Middle West.

2. The finer muds and clays that would normally develop over an area exposed for a long time to weathering, as was New England before the Ice Age, were largely scraped off by glaciers of earlier Pleistocene stages, and are now incorporated in pre-Wisconsin deposits.

3. The Buzzards Bay lobe which formed this moraine moved southeast across what had probably been a shoreline region before the sealevel fell. Thus it picked up enormous quantities of sand and silt when it scoured away the ancient beaches and shallow-water deposits that may have lain along the shore west of what is now Cape Cod Bay.

4. Vast quantities of outwash sand and gravel may have been spread over southern New England by glaciers of earlier stages. If so, ice of the Wisconsin stage would secure a large volume of such debris as it rode over these earlier glacio-fluvial deposits.

5. The moraine was built by readvance of ice over the western margin of the Mashpee pitted plain. Consequently, outwash sands that had been laid at the west edge of the pitted plain were picked up in the readvance.

Source of the Materials

Granitic types of rock make up most of the boulders in this moraine as well as a large number of the smaller stones. The average percentage of granitic types found in seven stonecounts taken at localities distributed along the moraine from north to south was 66 per cent (See Table 2b). This is decidedly higher than the average percentage of such types found in the Sandwich moraine. Quartzite and vein quartz pebbles make up 11 per cent and 8 per cent respectively of the stonecounts, and these percentages are likewise somewhat higher than for such types in the Sandwich moraine. Toward the southwestern end of the Buzzards Bay moraine many fragments and boulders of a coarse graphic granite were found. This type of rock was not observed anywhere in the Sandwich moraine. These differences in the content of the till of the two moraines and other differences to be described later make it fairly certain that the two lobes that deposited the moraines moved over regions differing appreciably in their bedrock. This is another reason for separating and distinguishing the two sections of Woodworth's "Falmouth moraine." Many of these stones were derived from ledges of granite that crop out on the land surface a few miles distant toward the northwest and north and thus indicate in a general way the direction from which the ice advanced.

Character of the Till

Nearly everywhere the till of this moraine is loosely consolidated and can be pulled apart easily with a hoe; but there are patches in which it is so compact and hard that local residents and well-diggers refer to it as "hardpan." Such material breaks into chips like a rock when struck with a hammer, and it is difficult to

sink a pick into it. "Hardpan" till of this nature can be seen in a roadside excavation on the north side of Blacksmith Shop Road, half a mile east of the State highway, Route 28. Here in 1939 a section 10 feet high was exposed, cut entirely in gray sandy till containing many subangular boulders that range up to 3 feet in longest dimension. The upper few feet of till here as elsewhere is stained a rusty brown by weathering processes which also loosened the material so that it is much less resistant to excavating tools.

Pseudo-stratification

The pit mentioned in the preceding paragraph, the cliffs at Nobska Point near Woods Hole, and exposures at several other localities show an inconspicuous streaking that resembles irregular layering or stratification in the compact till. This layering is produced by approximately horizontal, discontinuous, roughly parallel bands of silty material that range in thickness from that of a sheet of paper to about half an inch. They do not, however, represent distinct layers of water-laid material such as one might expect to find occasionally in the midst of till. Similar pseudo-stratification is found in till formed by modern glaciers and is interpreted as the result of packing and dragging of the material under the weight of moving ice. Such packing may be responsible, also, in part at least, for the greater compactness of the till at places where this lamination occurs. If this interpretation is correct, it follows that the till at such places was plastered on the land beneath the glacier rather than let down gradually by melting or evaporation of the ice.

Stratified Sediments in the Moraine

In addition to the stretches of gravelly moraine along its western side, there are areas within the Buzzards Bay moraine where the deposits are made entirely of outwash silt, sand, or gravel. These are generally enclosed within areas of till. They represent the deposits spread in local pools of meltwater that formed close to the frayed and fluctuating margin of the retreating glacier.

One of the larger areas of this type in the northern part of the moraine is located three-eighths of a mile southeast of Signal Hill and about three-fourths of a mile north of the Pocasset-Forestdale Road in the Pocasset quadrangle. Here a conspicuous, treeless glade at an altitude of 250 feet is crossed by Signal Hill Road and surrounded by irregular, wooded till knobs that rise 50 feet or more above the tiny plain. Very few erratics lie on the surface of this plain, whereas the bordering hills are thickly covered with them. A soil auger, an implement used for sampling subsurface materials by boring down through them and bringing up the material a few inches at a time, was sunk into this plain. It disclosed a fifteen-foot thickness of clean, yellow, medium to coarse sand containing a few pebbles.

In contrast with such a place where sand presumably overlies till, there are other localities where lake-bed deposits in the midst

of the moraine are covered by a thin veneer of till. One of these is on the Pocasset-Forestdale Road about a mile east of State highway, Route 28, near the center of the Pocasset quadrangle. Here a roadside pit has been excavated on the south side of the road to secure material for surfacing tennis courts. During the summer of 1939, the pit was free of slumped material, and an excellent vertical cliff-face was available for study. Here, the soil zone, four to six inches thick, overlies 18 to 33 inches of light-tan, sandy till containing many stones four inches or more in diameter and some subangular blocks a foot or more in length. This till rests on about 10 feet of thinly-stratified silt or fine sand with many layers of sticky clay. The clay is clearly a lake-bottom deposit. Here and there within it are a few, presumably ice-rafted, cobblestones and pebbles. Its use for surfacing tennis courts arises from the fact that it contains just enough clay to make it bind well and just enough silt to be drained readily. An auger hole sunk into the floor of the pit continued in till for three feet, then entered a zone, less than a foot thick, of thinly-layered silt and clay resting on sandy gravel or sandy till into which the auger could be driven to a depth of only two feet.

The layers in the upper 2 to 5 feet of the laminated silt have been almost doubled over on one another and contorted into arches the tops of which were apparently bevelled off by the overriding ice that laid the till above them. Some parts of the deposit were either frozen or compacted enough to act as more rigid units that broke and slid past one another when subjected to pressure from the readvancing ice.

A similar deposit of laminated silt and clay about 15 feet thick, overlain by sandy till, is exposed in several shallow pits on the north side of Brick Kiln Road, three quarters of a mile east of the State highway, Route 28, just within the western margin of the Falmouth quadrangle. The pits are excavated in an irregular area of flat, almost boulder-free land that covers about 100 acres and stands 120 feet above sealevel. This small plain is surrounded by knobs and kettles of boulder-strewn till. The thin layers of silt exposed here are also twisted and broken beneath the till cover. There are a few boulders embedded in the silt. The layers beneath one of them, seen in 1939, were bent downward, conforming to its lower surface, whereas those above its upper surface were horizontal. This stone must have been rafted out on a small iceberg and then dropped to the floor of the pond in which the silts were accumulating. The origin of the silt layers in these pits and their relation to the materials above and beneath them must be essentially the same as that indicated in the pit on the Pocasset-Forestdale Road. An auger hole in the bottom of the pit went into five feet of clean, well-washed sand and fine gravel. Another hole 100 yards east of the pit went through a ten-foot thickness of the laminated silt and then into about 2 feet of rusty sand.

Deposits such as these, consisting of alternating sheets of till and lake-bed materials, are precisely the sort of heterogeneous accumulations one would expect to find in a recessional moraine

constructed beneath and beyond the edge of a glacier, the margin of which shifted from time to time across a belt a mile or so in width.

Marine Fossils in the Moraine

Specimens of the material taken from the pit on Brick Kiln Road at 4, 6 and 8 feet below the overlying till were studied under the microscope by Arthur S. Knox, who reported that they contained minute fossils, fragments of the delicate skeletons of sponges and diatoms that were common in Pleistocene and Recent time and lived in marine or brackish water. The presence of such materials in glacial lake sediments that now stand over a hundred feet above the sea is not puzzling when we consider that these silts and underlying sands were originally deposited during construction of the moraine of which they appear to be an integral part and that the ice from which these sediments were derived had moved across a surface that had recently been a shallow sea floor. The remains of diatoms and sponges that had lived in a previous interglacial interval in the marine waters covering a locality north or northwest of this portion of the moraine were transported in the ice from some place where the advancing glacier plowed into the sediments in which the remains were embedded. Liberated when the ice melted, these fossils were washed into the pond along with silt and clay particles. In a sense they are simply "erratics" embedded in the glacial-lake silts.

Sandwich Moraine

Location and Character

A second belt of hummocky and relatively high terrain, known to the natives as the "backbone" of Cape Cod, lies close to the north side of the upper arm of Cape Cod approximately parallel to the shore of Cape Cod Bay. As stated on page 14, Woodworth considered this a part of the Falmouth moraine, contemporaneous with the other portion here designated as the Buzzards Bay moraine, but it is found that the till of the two morainic belts is distinctly different in some respects and it is believed that this east-trending moraine overlaps on the north end of the Buzzards Bay moraine. The name Sandwich moraine is, therefore, proposed for this important feature of the Cape, inasmuch as the moraine traverses for many miles the northern part of the town bearing that name.

Driving east from Sagamore to Dennis on Route 6 one has constantly on his right the irregular skyline of this "backbone" of Cape Cod. In the Sandwich quadrangle, the higher summits stand between 200 and 300 feet above sealevel; of these, Telegraph Hill, with its summit elevation of 292 feet, one mile south of Sandwich Village, is the highest point. Eastward along the moraine the hilltops decrease somewhat in altitude so that in the belt just south of West Barnstable the higher summits are between 150 and 200 feet above sealevel. Across most of the Sandwich quadrangle the moraine is more than a mile in width, but at the eastern margin it narrows to half a mile.

The surface is characterized everywhere by hummocks and hollows. The hollows, many of them true kettle-holes, are generally smaller than those of the pitted plain but much more numerous. The varied thickness of the till and the irregular surface upon which the moraine was laid also contributed to the unevenness of the landscape. In the area extending a mile or so east and southeast from Telegraph Hill in Sandwich, hummocks are elongated into rude ridges parallel to the belt of the whole moraine. These may represent material pushed up as a result of minor fluctuations of the ice front.

At most of its exposures the material in the Sandwich moraine is sandy till. A representative pit, on State highway, Route 130, opposite the entrance to the Telegraph Hill fire tower, shows a ten-foot thickness of till, including a few big angular blocks, and a few clumps of well-sorted sand such as are encountered occasionally in till. They may be the remains of frozen blocks of sand picked up by the invading ice from some outwash or beach deposit and incorporated in the till. Hard-packed, gray till or "hardpan," which is believed to be of the same age as the loose, sandy till elsewhere in the moraine, is exposed behind the farm at the north end of Gully Lane east of Sandwich Village and at a few other places.

Comparisons and Contrasts with the Buzzards Bay Moraine

Large erratics are generally less numerous on this moraine than on the Buzzards Bay moraine. In the region north of Telegraph Hill or along Maple Swamp Road near the center of the Sandwich quadrangle a person may travel almost a mile without seeing one. On the other hand, many areas in the southern part of the moraine next to the Mashpee pitted plain are liberally sprinkled with large blocks. Along Forest Street, south of West Barnstable and north of Popple Bottom Road, northeast of Farmersville, there are many boulders and blocks 2 to 20 feet long. The largest single erratic in this moraine, exclusive of the area of overlap on the Buzzards Bay moraine, may be seen one mile south of East Sandwich; it measures approximately 30 by 15 by 10 feet.

Explanation of the relative scarcity of boulders in this moraine may be found in the types of rock represented. Whereas more than 95 per cent of the large erratics in the Buzzards Bay moraine are granite or granite gneiss, from 5 to 20 per cent of the larger stones in the Sandwich moraine are composed of basalt or other volcanic rock. Granite ledges are notorious for yielding large blocks wherever they are crossed by moving ice. We may infer that as it approached Cape Cod the lobe of ice that formed the Buzzards Bay moraine passed over a larger area underlain by granite than did the ice that formed the Sandwich moraine.

Materials of pebble size, from one to three inches in diameter, also indicate a significant difference in the till of the two moraines. Fragments of bright red, arkosic sandstone and conglomerate, finely-laminated black and white quartzite, and black slate are common in the Sandwich moraine, whereas none of these rock types is found in the Buzzards Bay moraine. Moreover, the identification of

the rock types represented among 200 pebbles of such sizes collected at random at each of six localities in the Sandwich moraine shows different percentages of the types that are common to both moraines. For example, on the average only 45 per cent of the small stones in the Sandwich moraine are granite and the maximum for these collections is 57 per cent, whereas in the Buzzards Bay moraine the average is 66 per cent, and the minimum is 58 per cent. Basalt pebbles make up nearly 10 per cent of the smaller stones in the Sandwich moraine but only 3 per cent of those in the Buzzards Bay moraine. Other volcanic pebbles average 13 per cent in the Sandwich moraine and only 4 per cent in the Buzzards Bay moraine. Of course, the pebble content of any moraine changes from mile to mile of its length, but here the difference in rock content can be traced to within a mile or even a few hundred feet of the place where the two moraines join.

The south face of the Sandwich moraine overlooks the pitted plain along a sharp boundary that is easy to follow. South of Telegraph Hill and along Popple Bottom Road this front appears from the south like a high ridge strewn with scattered erratics. It is, however, complicated just north of Cape Cod Airport in the southeast part of the Sandwich quadrangle by subsidiary short ridges, as explained on page 25, of bedded gravel which extend obliquely out into the main pitted plain. These were probably formed near the ice edge prior to the deposition of the main moraine.

Although gravel pits and deep roadcuts are not so numerous in the Sandwich moraine as in the Buzzards Bay moraine, there is some evidence that both are essentially veneers of till, 5 to 30 feet or more in thickness, resting on disturbed glacio-fluvial sand and gravel. Roadcuts near the north edge of the moraine, on Quaker Meetinghouse Road and on Chase Road, reveal sandy till on bedded sand. The large kettle-hole traversed by Forestdale Road 0.7 mile southwest of Telegraph Hill in Sandwich and extending from the pitted plain into the moraine is analogous to similar kettle-holes along the front of the Buzzards Bay moraine and had a similar origin. A large mass of stagnant ice buried in the gravel of the plain did not melt until after the moraine had been deposited upon the north margin of the plain, following a readvance of the ice from the position in which it stood when the plain was under construction.

The northern part of the Sandwich moraine is a very irregular, commonly sandy, deposit at low altitude like that on the west side of the Buzzards Bay moraine. There is, however, a marked topographic break along the north boundary of the Sandwich moraine, even more conspicuous and continuous than that along the west side of the Buzzards Bay moraine. North of the Sandwich moraine lie areas covered with salt marsh, low sand plains, and a few distinct and entirely separate hills of the Scorton moraine.

Area of Overlap on Buzzards Bay Moraine

Time relations between the deposition of the Sandwich moraine and that of the Buzzards Bay moraine have been inferred from studies

in the region where the two moraines join, northwest of the apex of the Mashpee pitted plain. This area of overlap is as irregular and knobby as any parts of either moraine that lie to the south or east. The morainic topography extends northwestward as far as Great Herring Pond west of the Cape Cod Canal. At this blunt end it is less than a mile broad, but where the two moraines actually join it is three miles broad.

Many granite boulders are scattered over the surface of this western end of the Sandwich moraine. There are several clusters of such blocks along the transmission-line swath on either side of the Canal and at the southern edge of the Sagamore quadrangle. The largest block is Sacrifice Rock, half a mile northwest of Signal Hill fire tower near Bournedale. It has split into several huge slabs that lie against one another. The dimensions of the original single block were at least 30 by 20 by 15 feet. Cuts made by a tractor along the transmission lines and adjacent back roads have exposed sticky, tan to brown till with abundant buried blocks. Several gravel pits located in this area of morainic overlap disclose that stratified materials also constitute part of the deposits. On Canal View Road, both north and south of the boundary between the Pocasset and the Sagamore quadrangles, there are pits in bedded coarse gravel that includes waterworn boulders up to 4 feet in length. When the Cape Cod Canal was excavated through a low portion of this area of overlap and along the natural drainage line south of Great Herring Pond, it exposed sandy till with huge embedded blocks overlying bedded sand and gravel. As in the Sandwich moraine to the east and the Buzzards Bay moraine to the south, this till was spread over earlier glacio-fluvial deposits, and some glacio-fluvial deposition accompanied its formation.

Certain types of pebbles found in the Sandwich moraine but not in the Buzzards Bay moraine are seen in pits throughout this overlap area. These are chiefly chips of black slate, pink quartz-feldspar gneiss, red arkose, and laminated quartzite. The southern limit of occurrence of these pebbles is a rather sharp line just south of Kendrick Road at the north edge of the Pocasset quadrangle. The topographic break along this line, with higher hummocks and ridges lying to the south, adds emphasis to the idea that this is the southern limit of material put in place by the lobe of ice that deposited the Sandwich moraine. As this belt of what appears to be a westward extension of the Sandwich moraine cuts across the trend of the Buzzards Bay moraine and extends northwestward beyond it, the ice of the Cape Cod Bay lobe must have pushed forward to deposit the Sandwich moraine after the ice of the Buzzards Bay lobe had melted back from the position it occupied while the Buzzards Bay moraine was built. (See page 43 for further consideration of the time relations between advances of those lobes of ice.)

Identification of rock types among the pebbles in the till of this area of overlap indicates certain minor but significant differences in the composition of the till there, when compared with that farther to the east or south. The four pebble counts made in this western portion of the Sandwich moraine indicate that the proportions

of basalt, quartzite, and vein quartz are intermediate between those found to be characteristic of the rest of the Sandwich moraine and of the Buzzards Bay moraine. The percentage of granite pebbles is more like that in the Buzzards Bay moraine, but the proportion of volcanic pebbles is more like that of the Sandwich moraine. In other words, pebble types of the two moraines are mixed. This may be explained adequately as the result of overriding of the northern end of the Buzzards Bay moraine by southwestward-moving ice of the Cape Cod Bay lobe. As the ice front fluctuated back and forth in a fairly narrow belt, the debris that it was carrying was mixed with the debris into which it plowed or over which it advanced.

Deposits West of the Buzzards Bay Moraine

Gravels Derived from the Cape Cod Bay Lobe

As the thick, active ice of the Buzzards Bay lobe melted back from the Buzzards Bay moraine, a long, low depression sloping southwestward was uncovered between the western side of the moraine and the ice front (Fig. 7). Sometime later, while the Cape Cod Bay lobe was heaping up the ridges of the Sandwich moraine, its meltwaters were unable to escape through the high western part of the moraine onto the high apex of the Mashpee pitted plain and found an outlet southward along this trough. Sand and gravel deposits from that drainage now cover most of the surface from the vicinity of the Bourne Bridge southward through Pocasset, Cataumet, and North Falmouth to West Falmouth.

The belt of lower ground along which much of the meltwater escaped was not, however, a smooth, straight valley. It was littered with masses of stagnant ice that had been left by the Buzzards Bay lobe. Many of them did not melt away to form kettles until after the drainage from the north had ceased. Here and there between these blocks of ice were hills of debris formed by the glacier that now lay west of them. These were kames and bouldery knobs of till, some of which still protrude above the later glacio-fluvial deposits. Over the lower surfaces between the blocks of ice and these depositional hills there was probably a veneer of outwash spread from the northwest.

The meltwater that issued from the Cape Cod Bay lobe was, of course, charged with debris. It must have spread along many shifting channels that formed a complicated braided pattern as the streams found their way around obstructions and moved over the uneven land surface already floored with loose debris. Water may have been ponded for a time against obstructions of stagnant ice or hillocks of till. Material washed into such temporary pools would form small deltas with steeply-inclined stratification. Gradually the outwash materials from the north piled up and blanketed the earlier deposits almost completely; ponds were filled with sediment and disappeared; and a smooth plain of sand and gravel, sloping southwestward, was formed in this trough. This outwash plain had, however, the shape of a very narrow, partly-opened fan. On the north its high apex was

banked against and into the Sandwich moraine; its western side lay against the frayed margin of the ice sheet, and its eastern one against the floor of glacio-fluvial gravels beneath the Buzzards Bay moraine. The outer, convexly-curved margin of the fan lay somewhere out in what is now Buzzards Bay.

Only parts of the original sloping surface remain today, because the plain was indented by many kettle-holes and by gullies produced by later erosion. The highest and largest of the remnants comprises a few hundred acres, 110 to 130 feet above sealevel, east of the traffic circle at the southeast end of the Bourne Bridge. Southwestward from the bridge toward Pocasset many smaller gravel deposits with smooth, gently sloping tops rise to altitudes of only about 100 feet. Gravel knobs between Pocasset and State highway, Route 28, attain altitudes of 70 or 80 feet, and three miles farther southward in Megansett and North Falmouth the smooth tops of similar deposits have altitudes of only about 50 feet. Still farther south, narrow plains of gravel between Crocker Pond and West Falmouth lie only 20 to 25 feet above the level of Buzzards Bay.

Surface drainage began to dissect this plain soon after it was completed, and several furrows like those on the Mashpee pitted plain were formed. Southwest of Monument Beach two excellent examples of these have almost parallel courses. The lower end of the larger one, occupied by Pocasset River, is drowned. The narrow, branching, upper end of this valley begins near State highway, Route 28, about two and a half miles south of the Bourne Bridge. Five-eighths of a mile northwest of this furrow lies the other which heads in a kettle-hole at Clay Pond. A much narrower third valley extends from a group of kettles now occupied by ponds and cranberry bogs in South Pocasset southwestward to Squeteague Harbor at Cataumet. Many smaller and shorter gullies in the area between Buzzards Bay and the moraine likewise have southwestward courses. The shortest course for drainage from the upper ends of the three furrows to Buzzards Bay would obviously be almost due west instead of southwest. The trend of the valleys, therefore, confirms the idea that the original slope of the gravel plain was southwestward. Decrease in size of the outwash materials from coarse gravel at Bourne to medium and fine sand and gravel in West Falmouth also shows that the source of these sediments lay northeast near the Cape Cod Canal.

The furrows were formed before all the buried ice had melted away. Mill Pond, Shop Pond, The Basin, Freeman Pond, and Upper Pond, represent a chain of small kettles in the bottom of the Pocasset River valley, and smaller kettles occur in the bottoms of tributary gullies at the head of this valley near the highway. Cuffs Pond similarly represents a kettle in the floor of the narrow valley west of Cataumet.

Pebbles of types of rock which have been found in the Sandwich moraine but not in the Buzzards Bay moraine were encountered at a number of places in the gravels of the plain. For example, the chips of black and white laminated slate that are found almost everywhere in the Sandwich moraine are common in the gravels around Beaton Bog in South Pocasset, but in the Buzzards Bay moraine only a few hundred

yards away there are none of these chips. Pebbles of the same type were noted also at other pits in the area between the moraine and Buzzards Bay. These stones are a further indication that the materials composing the plain were spread southwestward from the Cape Cod Bay lobe.

The northern end of the plain rises to merge with the southwestern part of the Sandwich moraine in the area in which the latter overlaps the Buzzards Bay moraine. Slumping of materials around many deep kettles in this territory makes the distinction between sandy till and coarse gravel impossible. The boundary between material that should be designated as moraine and that which should be called outwash is, therefore, very indefinite. Much coarse gravel is exposed in pits along Canal View Road in the southwestern part of the morainic area. Large angular blocks scattered over the surface in this district also show that ice was nearby when these materials were deposited. High knobs made of gravel in this territory must have accumulated, therefore, more or less as kames. Patches of almost boulderless terrain and exposures of gravel between bouldery knobs of till, north and east of this, suggest that deposits made by the meltwaters may have extended far back into the heart of the moraine. Such complex interfingering of deposits and irregularity in topography are to be expected where outwash deposits have accumulated against a moraine while it was under construction, and these conditions are found in front of many modern glaciers.

Position of Buzzards Bay Lobe

The gravel fan of the Bourne region was built against thick ice on its west side. This is inferred from the fact that the high gravel deposits were not spread more directly westward into the trough of Buzzards Bay. As there are no indications that the present lower altitude of this broad trough was produced by erosion or slumping since the last glaciation, it is concluded that ice still occupied the trough and blocked westward drainage from the Cape Cod Bay lobe while the Sandwich moraine was deposited.

There is, furthermore, some evidence to show that parts of the ice margin stood just east of the present eastern shore of the Bay during accumulation of these gravels at Bourne. A prominent bluff extends northeastward across Monument Beach, beginning near the shore of Buzzards Bay at the southern end of Phinneys Harbor. West of it the land is low and sandy, but east of it lies an elongated, hummocky mound littered with boulders and underlain by till. Northeast of this a similar bluff 40 to 60 feet high can be traced for a mile or more along the east side of County Road northeast of Monument Beach. The material underlying the higher ground of this stretch is sand and gravel of the outwash fan. Farther north near Bourne Village, remnants of the gravel fan drop off abruptly from surfaces approximately 100 feet to low sand plains only 10 to 25 feet above sea-level. Such an irregular but almost continuous topographic break can not be attributed to erosional processes since the glaciation. Numerous large boulders litter the surface of the gravel deposits

and lie on this prominent northwest slope. It is believed;therefore, that the bluff represents the approximate line of contact between the receding edge of the Buzzards Bay lobe and the fan of outwash gravels from the northeast that was piled in front of it.

This ice-contact slope lies less than a mile south of, and is almost parallel in trend to, a similar bluff marking the western end of the Sandwich moraine half a mile east of Nightingale Pond in the Sagamore quadrangle. This irregular slope may likewise represent another part of the margin of the Buzzards Bay lobe. If so,ice covered the western third of the Sagamore quadrangle while the Sandwich moraine was accumulating and prevented the Cape Cod Bay lobe from pushing farther westward. In other words, the Buzzards Bay lobe had only receded about a mile or two from the western side of the Buzzards Bay moraine before the Cape Cod Bay lobe readvanced to form the Sandwich moraine. The interval of time between the deposition of the two moraines was, therefore, not very great.

Till Deposits or Ground Moraine

Deposits formed during recession of the Buzzards Bay lobe across the trough in which the narrow fan described above was built were not completely obscured by outwash gravels of the fan. Irregular knobs of till coated with boulders protrude at a number of places above the surface of remnants of the plain. The largest and highest of these forms an elliptical area of hummocky ground, a mile and a quarter in longest diameter, the northern end of which lies about a mile south of the southeast end of the Bourne Bridge. The summits of knobs in this area of till stand about 160 feet above sealevel and 60 to 80 feet above the surrounding remnants of gravel plain. Two smaller but essentially similar isolated massed of till in the Pocasset quadrangle occur in the western part of Monument Beach and along the shore east of Toby's Island. There are also numerous patches of lower, boulder-strewn ground in which sandy till may be seen at a few scattered exposures. These patches occur in the midst of gravel areas. Such till masses appear in the Pocasset quadrangle: at the northeastern side of Phinneys Harbor and around the marshes along Back River, in the central part of Pocasset, at Patuisset, and south of North Falmouth near Wings Pond. In the Woods Hole quadrangle similar bodies of till underlie the hills between the south end of Old Silver Beach and West Falmouth Harbor, all of Chappaquoit Island, a morainic hill about half a mile in diameter just west of Crocker Pond, and low areas at the southeast end of West Falmouth Harbor. A broad, low hill coated with large blocks that lies half a mile north of Nightingale Pond in the Sagamore quadrangle and is completely surrounded by gravels at lower elevations probably represents a similar protruding hill of till.

Some of the till masses listed above have rough surfaces full of kettle-holes. These hills must have been formed when irregular accumulations of till were let down upon the surface as the ice melted or evaporated. Other till masses such as the one west of the Sandwich moraine in the Sagamore quadrangle,hills south of Old Silver

Beach, and Chappaquoit Island have smoother surfaces with few kettles. This suggests that they were either plastered beneath the advancing ice or overridden by local readvances of its margin during the episode of recession.

Some of these till knobs were deposited as a veneer on glaciofluvial gravels that rise above the surrounding outwash from the Cape Cod Bay lobe. This may be seen in Falmouth Cliffs at the south end of Old Silver Beach, in the cliff at the northeast entrance to West Falmouth Harbor, and in a gravel pit on the south side of the hill at the north end of Wings Pond in the southeast corner of the Onset quadrangle. The sand and gravel of such floors must, of course, be outwash from the Buzzards Bay lobe.

Scorton Moraine

Location, Characteristics and Origin

The name, Scorton moraine, is applied in this paper to a group of elongate hills near the shore of Cape Cod Bay that stand in a discontinuous line or chain north of and essentially parallel to the Sandwich moraine. These hills, spaced at unequal intervals from Sagamore Village through Sandwich to Barnstable and surrounded by low plains of sand, include the hill at the northern edge of Sagamore Village, Sagamore Hill, Town Neck Hill, Spring Hill, Scorton Neck, and Scorton Hill. It is possible that other hills located in similar positions east of the areas studied represent a continuation of this Scorton moraine.

The surface of each of these hills is hummocky and irregular with small kettle-holes as much as 25 feet deep, but the topography is not so rough as that of most of the Sandwich moraine. Furthermore each segment of the Scorton moraine is sprinkled with angular blocks. As in the Sandwich moraine these are not closely packed nor are they very abundant, but some of them are of remarkable size. The subdued irregularity and the presence of these blocks suggest that these hills were formed at the edge of the ice sheet.

The structure characteristic of these hills is well exposed in a pit on U. S. highway, Route 6, at the south side and near the west end of Scorton Neck. At this locality, sandy till, 6 to 8 feet thick and including irregular clumps of sand, rests on bedded sand that contains thin seams of gravel. A small pit on the hummocky top of Spring Hill (1 mile northwest of East Sandwich) has been excavated in compact till. The soil auger disclosed that this till likewise rests on bedded sand a few feet below the floor of the pit. On the northeast slope of this hill, stratified sandy gravel has been excavated for surfacing a cranberry bog nearby. There are similar indications that both the hill north of Sagamore Village and Scorton Hill are also underlain by sandy gravel and veneered with till.

The manner in which the ice deposited this discontinuous moraine is not yet clear. Further study in adjacent areas must precede final inferences concerning the origin of the moraine and its associated deposits, but some conclusions and tentative working hypotheses can be developed from the information now available.

The Scorton moraine may never have been a continuous belt of moraine. If it had been, the amount of erosion necessary to remove all of it except the few scraps that remain today could not have occurred without producing effects observable in adjacent terrains. Such severe erosion would surely have cut deeply into the Sandwich moraine also. Yet only tiny gullies are found on the slopes of that moraine, and even its steep northern edge has been only slightly dissected. Some valleys should likewise have extended their headwater gullies deep into the hilly remnants of the Scorton moraine, but no such gullies are found. It is concluded, therefore, that the Scorton moraine was deposited originally as a discontinuous belt. The following discussion embodies one plausible hypothesis concerning a way in which that may have been accomplished.

If the ice retreated from the Sandwich moraine largely through down-wasting of the ice surface and consequent thinning of the ice sheet, it would produce a very ragged margin along which large masses of ice may have ceased to move at all. In and around these at the lowest places, glacio-fluvial gravels would be washed. Readvance of thicker portions of the ice sheet from the north would push the ice front forward as a deeply-indented, saw-tooth edge along which deposits would be concentrated in an irregular manner. Masses of inactive ice and patches of glacio-fluvial gravels between them, such as may be seen near receding glaciers in Alaska today, would be overridden by this advancing ice. Till might then be piled up or smeared on top of the patches of bedded sand and gravel. Later, when all of the ice had melted away, hills of gravel capped with till would remain where the gravel patches had been, and the lower ground around them where stagnant ice had stood might be covered unevenly with thin till let down from the ice. If later deposits of sand were spread by some agency over these lower areas and blanketed the till, the area would then consist of isolated, till-veneered hills of gravel standing like islands in a sea of sand. This is essentially the condition of the Scorton moraine today.

Low Sand Plains North of the Sandwich Moraine

The low sand plains between the hills of the Scorton moraine and the northern edge of the Sandwich moraine consist almost exclusively of uniform, sorted sand, as may be seen in several score of pits along roads in the northern part of Sandwich township. At few places is the material coarse enough to be called sandy gravel. The layering is regular and nearly horizontal in all pits, and no blocks are embedded in these deposits. The surface in some patches, a few acres in area, is flat or imperceptibly inclined; elsewhere it is gently irregular with swells and hollows.

Apparently the deposit was laid in a broad trough uncovered between the diminishing ice sheet on the north and the high Sandwich moraine on the south. The fine bedding and sorting show that this is a current-borne deposit, and it suggests that the material was deposited so far from the main ice sheet that only the fine, washed material remained. Scattered small kettle-holes mark places where ice masses were trapped beneath the sand.

The surface of the undulating sand plain is indented with shallow grooves resulting from erosion by small streams. This is evident at the heads of certain estuaries in the salt marshes which fringe Cape Cod Bay. In Sandwich these extend like narrow fingers into the low sand plain. The pattern they make is that of valleys cut by streams on a gentle and uniformly resistant slope. Such erosion also lowered the surface level of the intervening divides or remnants of sand plain, especially where the valleys are large and close together.

The northward slope of remnants of the plain which lie between converging valleys may also be attributed to this dissection. Since this erosion the lower ends of all these valleys have been submerged by the rise in sealevel, and salt marshes have clogged the long shallow bays. Sand has been cut by waves and swept by shore currents from exposed headlands to build protecting beaches like Town Neck and Springhill Beach between these salt marshes and the open water of Cape Cod Bay, and winds have transported sand from the beaches to form the Barnstable dunes.

Ellisville Moraine and Wareham Pitted Plain

Location, Boundaries and Character of the Ellisville Moraine

A belt of very irregular topography which stands generally higher than the adjacent countryside and is dotted with thousands of erratic blocks extends northwestward from the shore of Cape Cod Bay near Ellisville into the area north of the Sagamore quadrangle. Maps of the Manomet and Plymouth quadrangles show that similar topography continues northwestward for several miles beyond the territory thus far studied. Because of its linear extent and because it is made primarily of sandy till, the writers have called this belt tentatively the Ellisville moraine. The geographic location of this deposit, the degree of weathering of its materials, the lack of compaction of the till and the very slight degree of modification of its original surface by erosion indicate that this is another recessional moraine formed during the same glacial stage (the Wisconsin) as the moraines on the Cape to the southeast.

The boundaries of this moraine are more difficult to locate with certainty than are those of the Buzzards Bay and Sandwich moraines. This is especially true on the southwest side where no distinct ridge marking a moraine front can be observed. Instead, the boulder-strewn moraine seems to merge irregularly with the much pitted northern edge of a large outwash plain. This is designated tentatively as the Wareham pitted plain, and its surface slopes rise in places to the higher levels of the morainic area. Unfortunately, there are few cuts along roads or pits around cranberry bogs to disclose the materials in this critical territory. The soil auger could not provide the information needed to distinguish sandy till from gravel because it will not penetrate material that carries pebbles more than two inches in diameter; and most of the subsurface deposits in this vicinity contain an abundance of stones of that size or larger. Slumping of sand and gravel layers around many kettles has

destroyed stratification and sorting, so that it is virtually impossible to distinguish such material from the sandy till of the moraine. Even the presence of large blocks or boulders in a deposit does not guarantee that the material is till because such erratics could easily have become lodged in outwash gravel from nearby ice. The southern margin of the Ellisville moraine is, therefore, probably much more irregular than has been indicated on the map. To plot it in detail would require the digging of many long trenches, and this would be a far more costly operation than is warranted by the purposes of the present investigation.

An uneven and indistinct boundary like the one just described is found at some places along the margins of present-day glaciers in Alaska where ice oscillates across a narrow zone for a time, building a moraine in front of which an outwash plain develops simultaneously. During construction of the deposits at such places, masses of stagnant ice, either isolated from the main mass or protruding beyond it in irregular tongues, are buried by outwash or by till. Sand and gravel washed out of active ice accumulate in places on top of the till laid by stagnant ice and are then covered with more till when the ice readvances into the same territory. Consequently, a complex interfingering of glacial and glacio-fluvial materials is produced. Finally the outwash plain is built up so high that its materials are deposited in places within the morainic area and fill some of the hollows. Melting of the buried ice then causes so much slumping in the zone of contact between the moraine and the outwash plain that the relations of the deposits become still more complex and confusing, and any ridge-like elevation that may once have existed along the front of the moraine is destroyed.

The topography in the zone between the main body of the Ellisville moraine in which till is exposed and parts of the Wareham pitted plain in which undisturbed gravel may be observed is essentially like that produced under the conditions outlined above. It is believed, therefore, that this moraine and its bordering outwash plain were formed simultaneously in a similar manner. The moraine was not superimposed on the margins of a pitted plain by readvance of ice, as were the Buzzards Bay and Sandwich moraines, but was constructed when the continuous northward retreat of the ice front was halted for a considerable interval during which its edge fluctuated over the area now covered by the morainic deposits.

On its northern side, about half a mile southwest of Briggs Reservoir, the Ellisville moraine has a rather prominent, steep, bouldery margin, which can be traced easily as a continuous bluff for more than a mile. East of this a similar area of higher ground (which may or may not be part of the moraine) covered with boulders curves northeastward and includes Hio Hill and the hills northeast of it through Vallersville; but the bluff that forms their northern boundary is not as steep, continuous, or straight as the one described in the preceding sentence. The smoother topography of Hio Hill suggests that its origin was somewhat different from that of its surroundings, - a possibility that has not yet been thoroughly investigated. The hill is located within a zone of irregular topog-

raphy, however, and the number of large blocks scattered over its surface indicates that it is at least veneered with, if not completely made of till. For the present, therefore, the possibility is entertained that this zone may belong in the Ellisville moraine. The hills northeast of Hio Hill are irregular and bouldery, and they rise abruptly above the sandy terrain that lies northwest of them. They seem to be continuous with and therefore to belong to the moraine. If this interpretation is correct, the northern margin of the moraine continues as a slope that follows for about a mile the trend of Ship Pond Road southeast of Morey Hole. This northward-facing slope was formed after the edge of the ice had stood against the moraine in this vicinity for some time. As the glacier withdrew, the till in contact with it slumped to form a steep slope. Lack of any appreciable gully formation on such a slope is a strong indication that no great interval of time has elapsed since it was created.

The lower ground north of the Ellisville moraine in the north central part of the Sagamore quadrangle is floored with well-stratified sand and gravel. Its surface is pitted, and patches of sandy till or slumped gravel occur in the side walls of the kettles. This is interpreted as an area of glacio-fluvial deposits which were spread after the formation of the Ellisville moraine as the ice receded to some position to the north or northeast.

From the shore of Cape Cod Bay at Salt Pond an irregular bluff that faces northeast can be traced through Ellisville and Eastland Heights to the intersection of Ship Pond Road with Old Sandwich Road west of Hio Hill. At Ellisville this slope lies on the southwest side of Old Sandwich Road. Its northwestward trend is interrupted by the large kettle that contains Savery Pond, but the bluff swings north across the road at Eastland Heights and then curves southwestward to cross the road again a quarter of a mile south of the end of Hio Hill. Compound kettles containing Big Dugway Pond and Black Pond form deep reentrants in this bluff, but it straightens and becomes prominent again on the west side of the road and continues northward to the road intersection. With the exception of Hio Hill, the land northeast of this for some distance, lies at generally lower altitudes though it is almost morainic in character. The bluff is thus a distinct topographic break, much like that along Ship Pond Road, and it probably marks a position of the ice edge during construction of the Ellisville moraine. There may be justification for considering this, in fact, as the northern margin of the moraine. Reasons for not doing so and for including tentatively the lower till-covered area northwest of it in the moraine are given in the following paragraphs.

A belt of morainic topography studded with boulders extends northward from Ellisville through Vallersville to the northern boundary of the Sagamore quadrangle. It covers an area from a half to three quarters of a mile wide, west of the shoreline of Cape Cod Bay. Altitudes in this belt are lower than in the moraine south of Ellisville, and the kettles are not as deep. Numerous gravel pits in this area show a veneer of sandy till overlying layered sand and gravel; other pits are excavated wholly in sand. The till veneer

and abundant erratics were deposited during final recession of the ice northeastward from the higher ground of the Ellisville moraine. The sand and gravel may represent, in part at least, a floor of earlier glacio-fluvial deposits over which the ice had advanced before it built the higher ground of the Ellisville moraine. Such a floor beneath till is well exposed in cliffs along the shore on the east side of Indian Hill, half a mile northeast of Vallersville, and may continue for some distance beneath adjoining areas. Part of these stratified materials may have been formed during fluctuations of the borders of the ice while it was producing the moraine. The sand that underlies patches of this area over which there is no till may have been spread between mounds of till after the ice had withdrawn permanently northeastward.

Southeast of Hio Hill there is an almost boulder-free area that is lower and smoother than the terrain surrounding it. This trough is roughly triangular with an apex about a quarter of a mile north of Savery Pond and its base between Hio Hill and Long Swamp. Except for the fact that its surface area is much larger and is full of small knobs and kettles, this area resembles the local patches underlain by gravel that are commonly found within the Buzzards Bay moraine. The kettles demonstrate that there were ice blocks beneath it after the ice withdrew. This precludes the possibility that this surface represents part of the floor over which the ice moved, for if kettles had existed during the glacial advance, they would have been filled. This area is therefore interpreted as a glacio-fluvial deposit that was formed almost contemporaneously with the adjacent hillocks of till during accumulation of the moraine.

The irregular knobs of till in the area northeast of the bluff that extends from Salt Pond through Ellisville are essentially continuous with the materials in the higher parts of the moraine. They were deposited only a short time after the bluff was produced. If the interpretation is correct, that the slope which forms the northwest border of this area (approximately along Ship Pond Road) marks a contact of the ice edge with the materials southeast of it, then the main body of the glacier must have stood close to this area, even after most of these hummocks of till were in place. In other words, the till deposits of this lower terrain were formed during the same general episode in the history of ice recession as those in the higher terrain. They may therefore be included in the territory mapped as the recessional Ellisville moraine.

Extent and Character of the Wareham Pitted Plain

Only the southeastern portion of the Wareham pitted plain is included in the Sagamore quadrangle. This broad outwash plain extends southwestward from the Ellisville moraine to the shores of Big Buttermilk Bay, the northeast extension of Buzzards Bay, in the southwestern corner of the Sagamore quadrangle. Its extent westward is not known at present, but the topography of adjacent areas shows that such a plain covers most of the adjoining Wareham quadrangle, extends into the southwestern corner of the Manomet quadrangle, and occupies

much of the southern part of the Plymouth quadrangle. If the gravels between Great Herring Pond and Cape Cod Bay are included as part of the broad area of outwash materials that were deposited at approximately the same time as the construction of the Ellisville moraine, it is clear that the Wareham pitted plain once extended southeastward beyond the steep wave-cut cliffs at the shoreline.

Peaked Cliff, a high point on the shoreline of Cape Cod Bay half a mile north of Sagamore Highlands, is the apex of a more or less conical mass of outwash gravel that underlies the area east of Great Herring Pond. Slopes of the surface away from this apex, although they are interrupted by many kettles, suggest that the materials were spread generally southwestward from a source (ice border) that lay somewhere east or northeast of Peaked Cliff.

The outer margin of this fan of glacio-fluvial material is irregular. It lies against the Sandwich moraine on the southwest and against the Wareham pitted plain on the west and northwest. Although in general the altitudes of this cone are below those of the pitted plain where the two come in contact, other features indicate that the outwash in both these areas was deposited from ice that lay to the northeast during approximately the same interval of time. Furthermore, as an outwash plain is ordinarily a compound unit built up by the overlapping of several cones of outwash, it seems logical to include this eastern cone in the Wareham pitted plain.

The dimensions of this pitted plain are comparable to those of the Mashpee pitted plain, but its surface is much more irregular and pitted. Apparently, many large bodies of stagnant ice lay in a broad lowland area, the southern end of which is now occupied by Buzzards Bay, and remained there until buried beneath a great apron of outwash that spread southwestward from the Cape Cod Bay lobe. South of Long Pond Village, as well as west of the south end of Great Herring Pond, and also in the area between Little Sandy Pond and Weeks Pond in the Sagamore quadrangle, there are remnants of a fairly smooth surface that slopes southward and southwestward. More extensive remnants scored by long furrows occur through the central part of the Wareham quadrangle. These patches of higher ground suggest that the pitted plain once had a continuous, smooth surface that has been almost destroyed because of the melting away of buried ice masses.

Despite the moraine-like appearance of its pitted surface in the Sagamore quadrangle, the southwestward slope of the plain is indicated by a gradual change in the heights of smoother tracts between kettles which range in altitude from more than 150 feet near Long Pond Village and more than 200 feet on Mountain Hill near Ellisville to sealevel at Big Buttermilk Bay.

The Wareham pitted plain is not shaped like a fan with a single apex and a convex outer margin. Its surface slopes seem to converge toward several high areas along the southwest side of the Ellisville moraine, and suggest that outwash was fed from several major sources along the ice front. To locate the exact positions of these sources is difficult, however, because so many large kettles have developed in the zone bordering the moraine. A gradual but irregular change southwestward in the size of constituents in the gravel, from coarse

sand and coarse gravel with numerous boulders near the moraine to medium and fine sand with small and relatively few boulders and few streaks of coarse gravel at the shoreline, shows that the materials were supplied from the northeast.

Abundance of Buried Ice Blocks

Furrows that are essentially similar in shape and origin to those on the Mashpee pitted plain extend generally southwestward across the gently sloping remnants of the original surface. The furrows are most continuous through the central part of the Wareham quadrangle where a number of them have remarkably parallel courses and are closely spaced. Valley Road southwest of Great Herring Pond is located in the bottom of the longest furrow in the Sagamore quadrangle. Two shorter ones lie a few miles northwest of this, one reaching northward for about two miles from Long Duck Pond, and the other extending in several branches northward from Ware Bogs almost to Wareham Road. Many kettle-holes developed after the furrows had been cut by surface drainage on the plain. Hollows half a mile or more in diameter and from 20 to more than 50 feet deep, some of them occupied by ponds, now lie across the furrows, and smaller pits have developed in the smooth and generally flat bottoms of these grooves. On their seaward ends the furrows become narrow estuaries, like those on the Mashpee pitted plain, created by the rise of sealevel.

Across the northeastern part of the pitted plain a series of elongate kettles, some of which are exceptionally large, form an almost continuous depression curving southward to the Cape Cod Canal at Bournedale. Ponds fill the bottoms of the larger ones; from north to south these are: Gallows Pond, Little Long Pond, Long Pond, Bloody Pond, Little Herring Pond and Great Herring Pond. The alignment and elongated nature of these depressions suggest that they lie along the trend of what was formerly a lowland or valley, now partly filled with Pleistocene deposits. Stagnant ice lay in this valley a considerable length of time. Some of it was there before the Sandwich moraine was built, as is indicated by the fact that the southern part of the kettle containing Herring Pond extends into the blunt end of the moraine at Bournedale. All of this buried ice must have remained until after the glacier had receded and built the Ellisville moraine, for the smooth surface of the Wareham pitted plain was deeply indented when the ice finally melted to produce this unusual chain of kettles.

Till Clumps

Clumps and larger masses of sandy till, containing erratics, occur at several places in the midst of outwash gravels of the pitted plain. All these till masses are on the margins of kettles, and the till lies upon outwash gravels. They were, therefore, deposited locally in a manner such as was outlined for till clumps of the Mashpee pitted plain by blocks of ice responsible for the kettles. The most notable of these masses in the Sagamore quadrangle occurs around the western end of the compound kettle-holes in which the Century Bogs

have been developed. The till can be seen lying on well-stratified sand and gravel at several exposures along the margins of the bogs. In contrast to the clumps of the Mashpee pitted plain, however, these till masses are larger, cover several acres adjacent to the bogs, and contain many large erratic boulders.

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1) Bryan, K., New criteria applied to the glacial geology of southeastern Massachusetts (abstract): Geol. Soc. of America Bull., vol. 43, p. 176, 1932.

2) Chute, N. E., Geology of the coastline between Point Gammon and Monomoy Point, Cape Cod, Massachusetts: Commonwealth of Mass. Dept. of Public Works, Special Paper No. 1, 1939.

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7) Woodworth, J. B., and Wigglesworth, E., Geography and geology of the region including Cape Cod, the Elizabeth Islands, Nantucket, Martha's Vineyard, No Man's Land and Block Island: Museum of Comp. Zool., Harvard University, Mem., vol. 52, 1934.

PUBLICATIONS

The following reports on investigations under the cooperative geologic project of the Massachusetts Department of Public Works, and the United States Department of the Interior, Geological Survey, have been published or are in process of publication. Reports published for distribution are obtainable through the Massachusetts Department of Public Works, 100 Nashua Street, Boston, Massachusetts.

Annual progress reports

Cooperative geologic work in Massachusetts for the year ending December 31, 1938: by L. W. Currier.
Cooperative geologic work in Massachusetts for the year ending December 31, 1939: by L. W. Currier.
Cooperative geologic work in Massachusetts for the year ending December 31, 1940: by L. W. Currier.

Special papers

1. Geology of the coastline between Point Gammon and Monomoy Point, Cape Cod, Massachusetts: by N. E. Chute. (Copies available through the Massachusetts Department of Public Works).
2. Gravel deposits of the Granville quadrangle: by W. S. White. (Copies may be consulted in library depositories).
3. The seismic method for determining depths to bedrock, as applied in Lowell quadrangle, Massachusetts: by F. W. Lee, F. C. Farnham, and A. Raspet; with an introductory chapter on the geology of the Lowell quadrangle, by L. W. Currier. (Copies available).

Bulletins

1. Preliminary report on the geology of the Blue Hills quadrangle: by Newton E. Chute.
2. Preliminary report on the geology of western Cape Cod: by Kirtley F. Mather, R. A. Goldthwait, and L. R. Thiesmeyer.
3. Geology of Quabbin Reservoir area: by Robert Balk. (Manuscript copies at library depositories).
4. Preliminary report on the geology of Northfield quadrangle: by Robert Balk. (Manuscript copies for library depositories in preparation).
5. Pegmatites of Massachusetts: by Marland P. Billings.
6. Gravel and sand deposits of Ludlow, Granby, Amherst and adjacent areas: by Robert R. Wheeler. (Manuscript copies at library depositories).

Notes

Annual reports are mimeographed and a small number are available for distribution. Copies are sent to the State librarian, to public libraries at Boston, Worcester, and Springfield, and to colleges and universities. They may also be consulted at the office of the Department of Public Works, Boston, and the library of the Geological Survey, at Washington, D. C.

Bulletins and special papers include some reports that are published (in mimeograph form) for general distribution, and others that are deposited as manuscript copies at the public libraries in Boston, Worcester and Springfield, with the State librarian at Boston, at the office of the Department of Public Works, Boston, and at the library of the Geological Survey, Washington, D. C. The public may consult the manuscript copies at these library depositories. Unless otherwise indicated a limited number of the reports is available for public distribution through the Massachusetts Department of Public Works. Published reports may also be consulted at college libraries throughout the State.

Some or all of the reports now available only in manuscript form may be published at some future time, and will then bear the publication numbers assigned to them as manuscript copies.

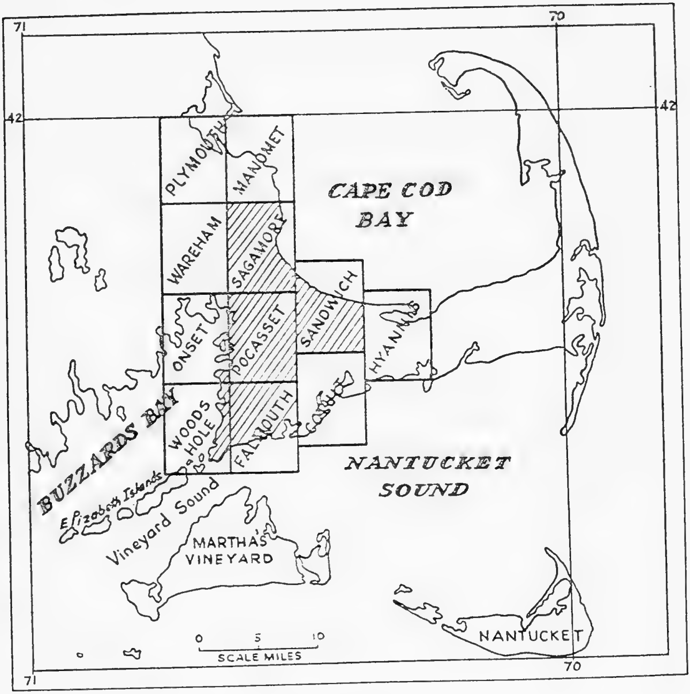

FIGURE 1

OUTLINE MAP OF SOUTH EASTERN MASSACHUSETTS, SHOWING QUADRANGLES INVOLVED IN THIS REPORT. SHADING INDICATES QUADRANGLES INCLUDED IN GEOLOGIC MAPS, PLATES I AND II.

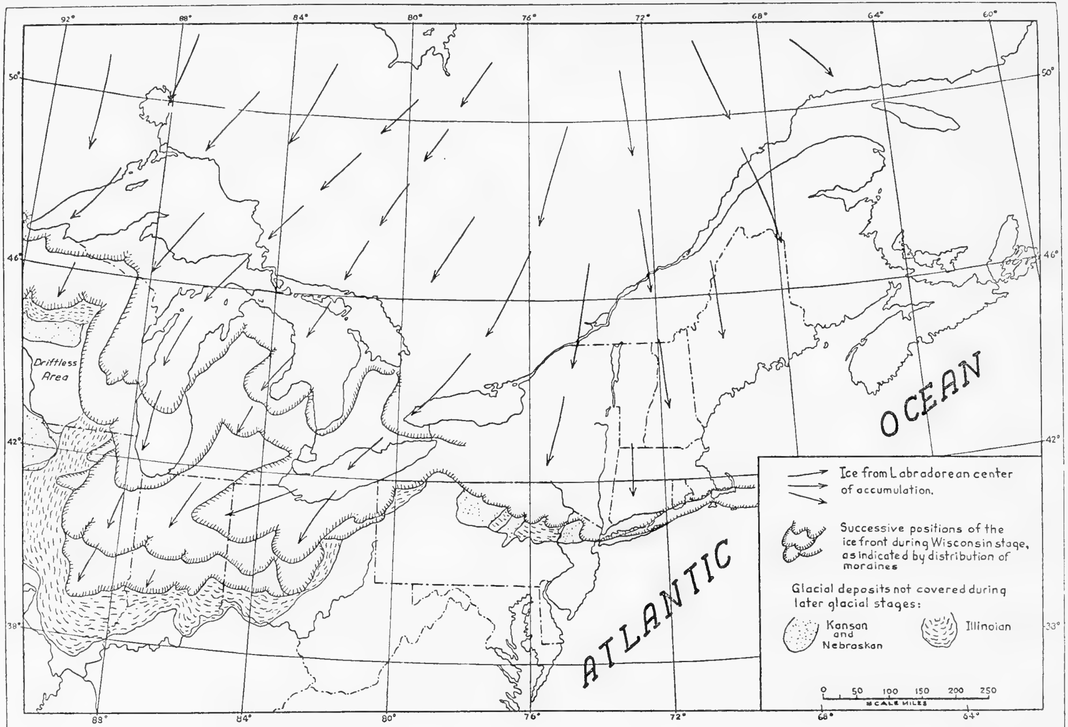

FIGURE 2
SKETCH MAP OF NORTHEASTERN NORTH AMERICA SHOWING AREAS THAT WERE COVERED BY PLEISTOCENE ICE SHEETS.
(GEOLOGY BY LEVERETT, FULLER, WOODWORTH, AND OTHERS)

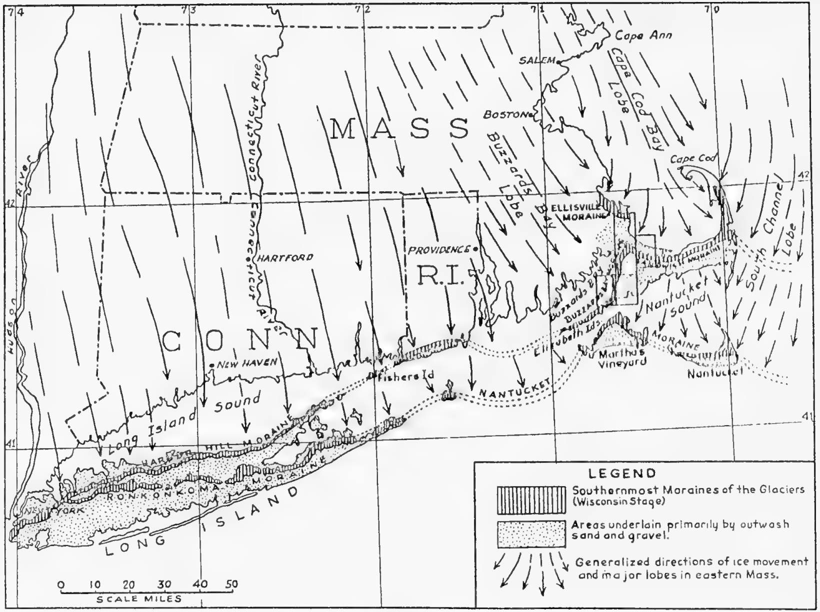

FIGURE 3

SKETCH MAP SHOWING MORAINES AND OUTWASH PLAIN AREAS OF SOUTHEASTERN NEW ENGLAND AND LONG ISLAND. THE INTERPRETATIONS OF GLACIAL FEATURES OUTSIDE THE QUADRANGLES SHOWN IN OUTLINE ARE THOSE OF M.L. FULLER, J.B. WOODWORTH, W.C. ALDEN AND J.W. GOLDTHWAIT. THE QUADRANGLES OUTLINED CORRESPOND TO SHADED AREAS OF FIGURE 1.

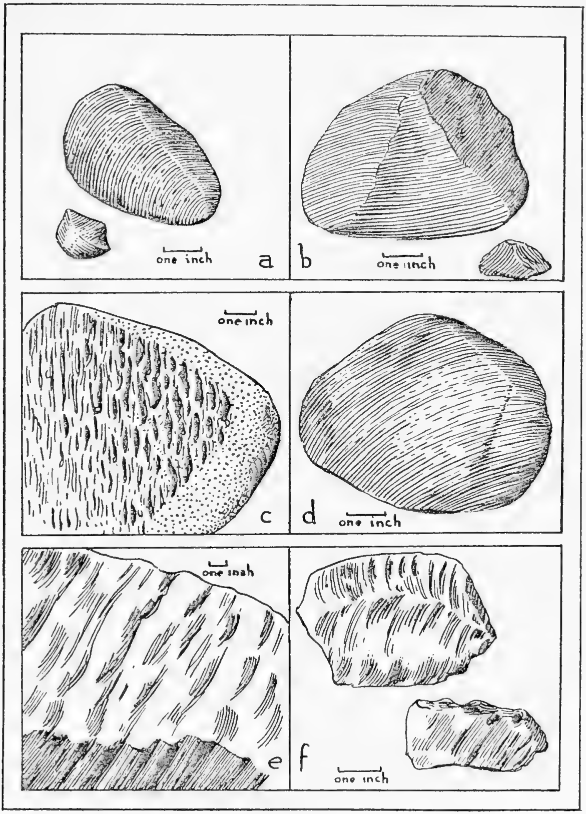

FIGURE 4

SKETCHES OF WIND-CUT STONES FROM GLACIAL DEPOSITS OF CAPE COD.

A-ROUNDED COBBLES BEVELLED BY WIND-CUT FACETS.
B-PYRAMIDAL VENTIFACTS FORMED BY INTERSECTING FACETS.
C-DEEP GROOVES AND FURROWS ON BOULDER.
D-ANGULAR VENTIFACT ROUNDED BY LATER ABRASION.
E-DEEP FLUTING ON GRANITE BOULDER.
F-PARALLEL GROOVES AND PITS.

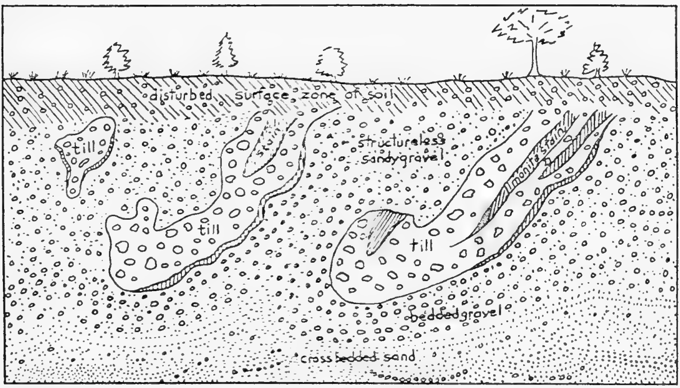

FIGURE 6

DIAGRAMMATIC SKETCH OF TILL CLUMPS IN GRAVEL PIT NEAR TEATICKET

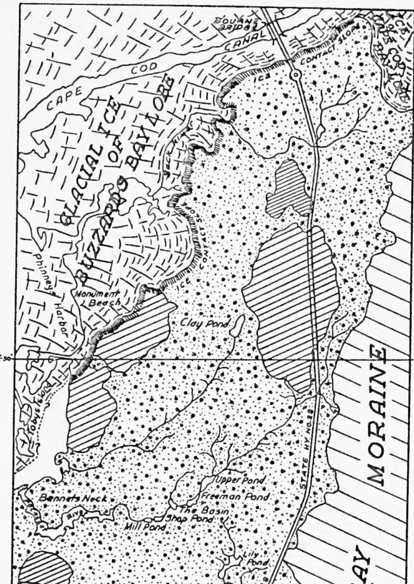

FIGURE 7

SKETCH MAP OF PART OF POCASSET QUADRANGLE SHOWING PRESENT DRAINAGE IN AREA OF GRAVEL FAN THAT WAS DEPOSITED BETWEEN THE BUZZARDS BAY MORAINE AND THE BUZZARDS BAY ICE LOBE IN A POSITION OF ITS RETREATAL STAGE.